Fold-Thrust Geometries - Is There a Right Model?*

By

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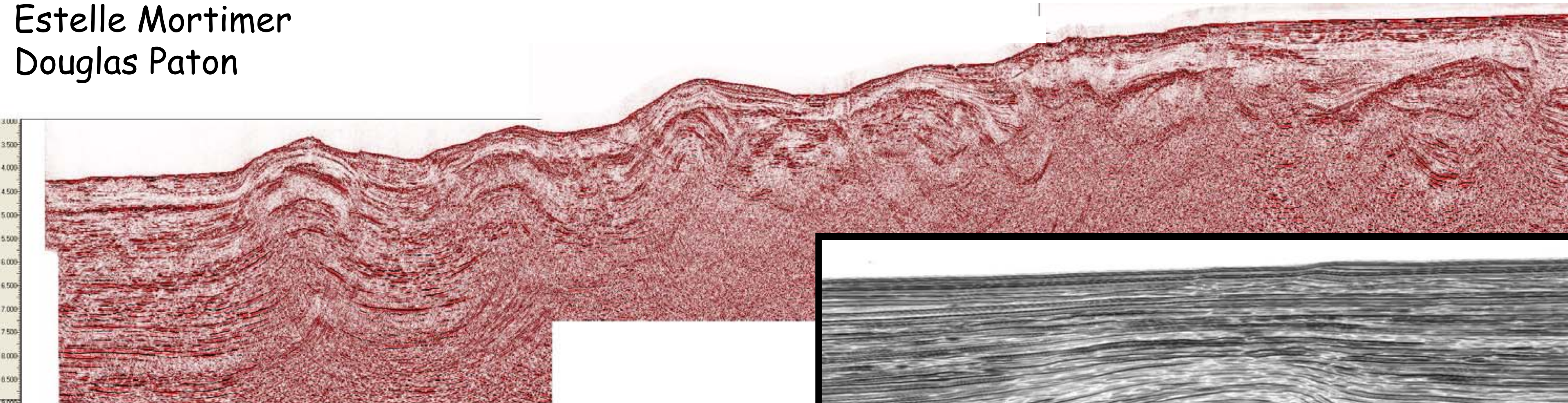
Abstract

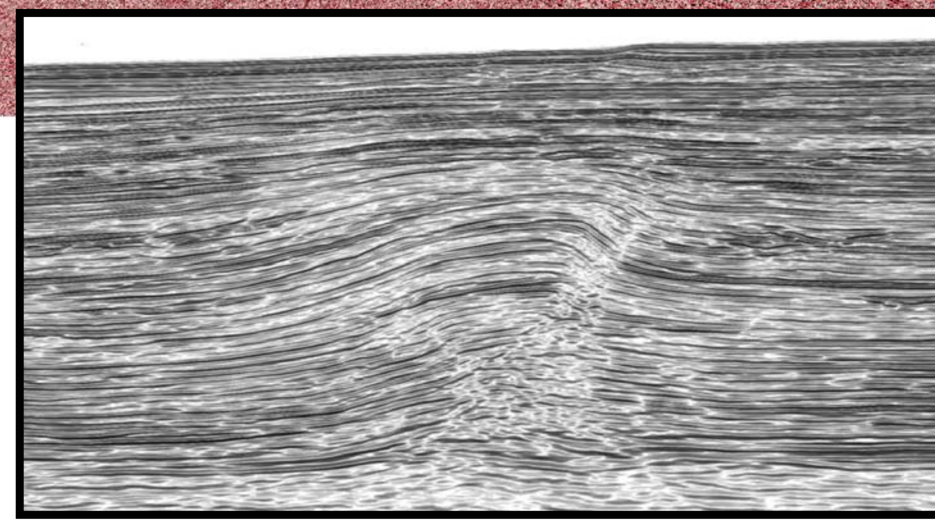
Fold and thrust structures offer interpretational challenges, even when well-imaged in 3D seismic volumes. There are several end-member kinematic models for folding in compressional belts, including fault-bend, tip-line and detachment structures. On individual 2D profiles, the consequences of particular structural interpretations, either using ideal end-member behaviours or composite styles, can be explored using combinations of graphical restoration and forward models. It is well known that simple 2D restorations can serve to validate structural interpretations and thus begin to reduce interpretation uncertainty. Further tests can include the ability to model the patterns of growth strata. In three dimensions, serial section approaches can be used to test for lateral strain compatibility. Where strain paths and deformation mechanisms are appropriate, 3D forward models and restorations can be applied. While all these strategies can be applied to assess the options for stratal offsets and deformations of surfaces, where input data are restricted to seismic alone, the role of distributed strain on structures below seismic resolution commonly represents uncertainty that is difficult to evaluate. In this presentation, the outcomes of different restoration and modelling strategies are compared for an individual structure imaged on 3D seismic data (from deep water Nigeria). While restoration and modelling can eliminate (or at least risk as being unlikely) geometrically unbalanced options, there remain a range of competing, viable structural interpretations. A key component of assessing this uncertainty lies in capturing a broad range of viable alternatives, best achieved through using different workflows and multiple interpreters with difference experience and backgrounds.

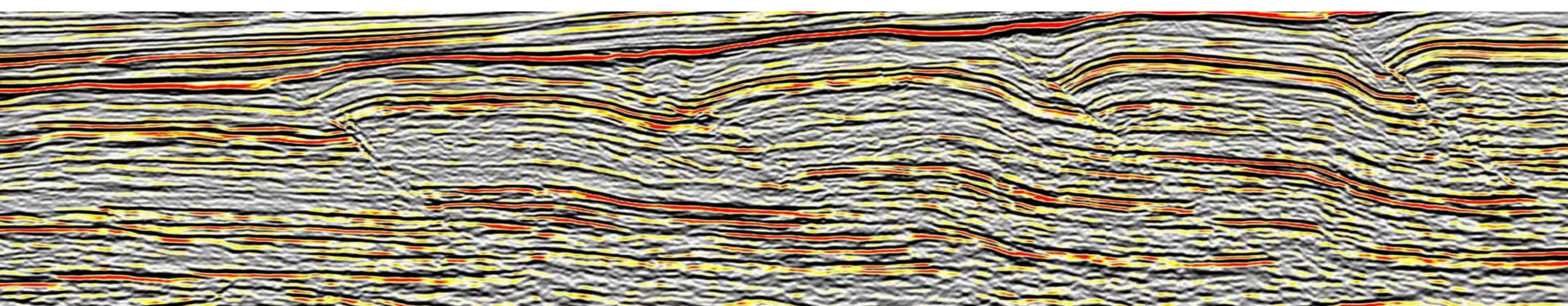
Fold-thrust geometries - is there a right model?

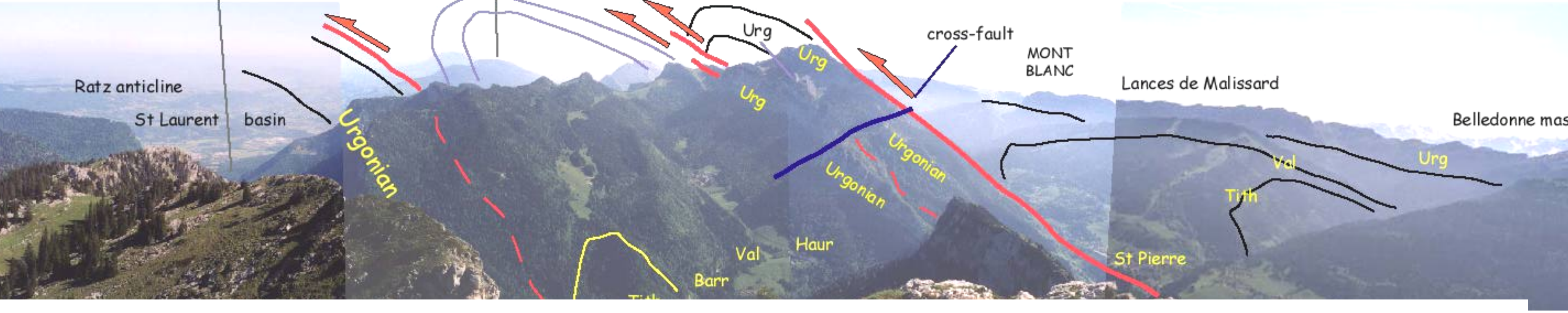
Rob Butler
Clare Bond
Estelle Mortimer
Douglas Paton

University of Aberdeen
University of Leeds
VSA
The Virtual Seismic Atlas
Midland Valley





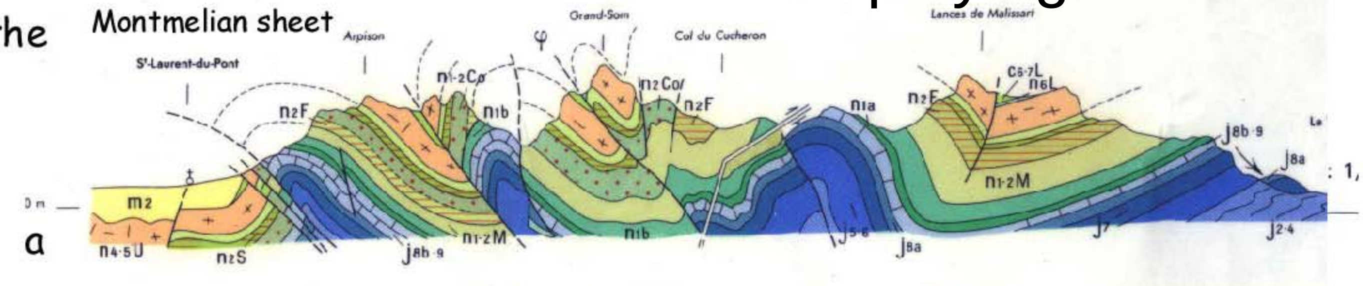


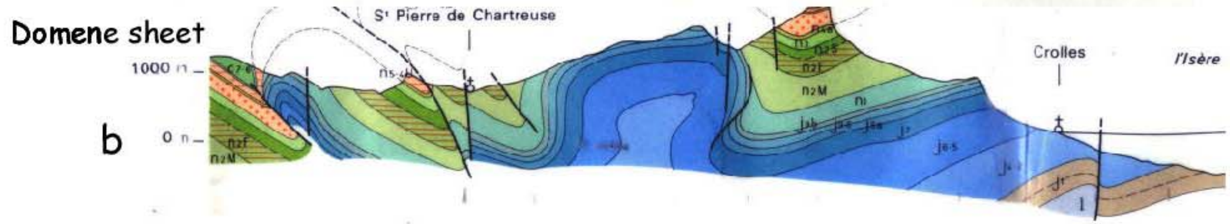


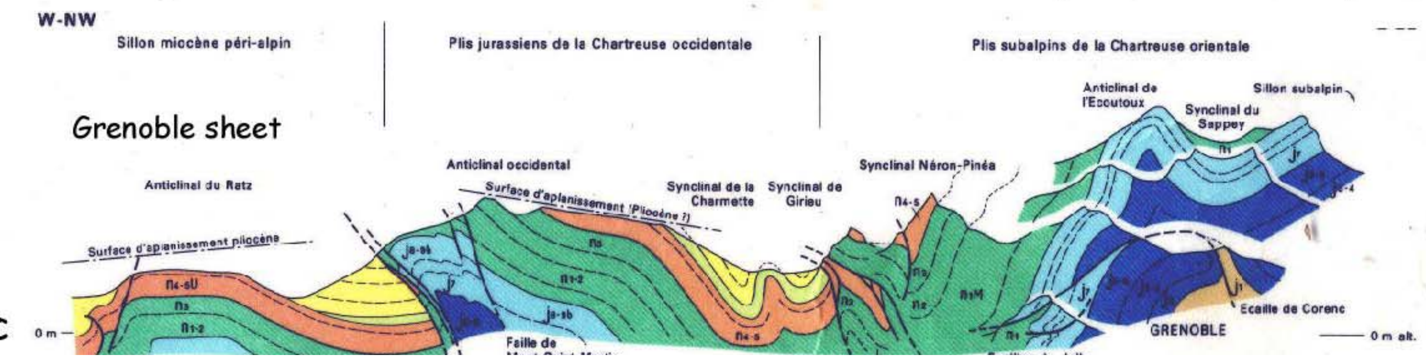
Models - playing with outcrop

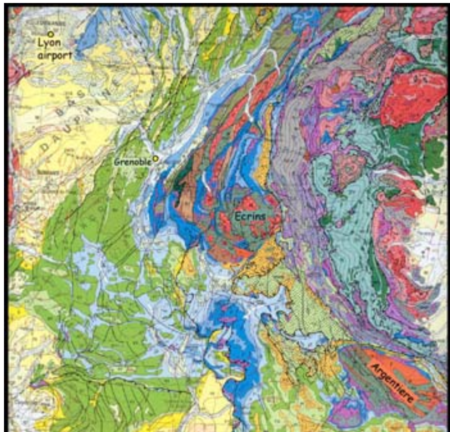
Cross-sections through the Chartreuse massif from published maps

2 km
v=h

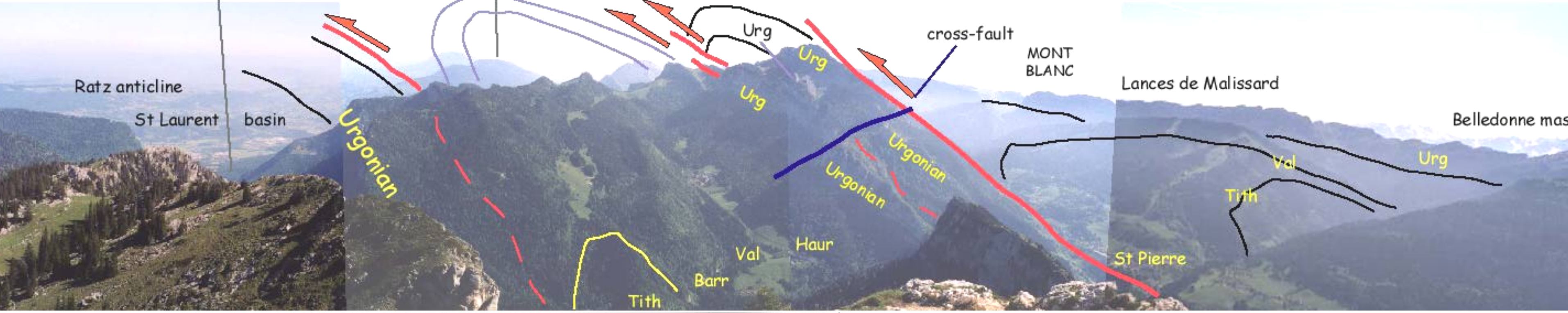


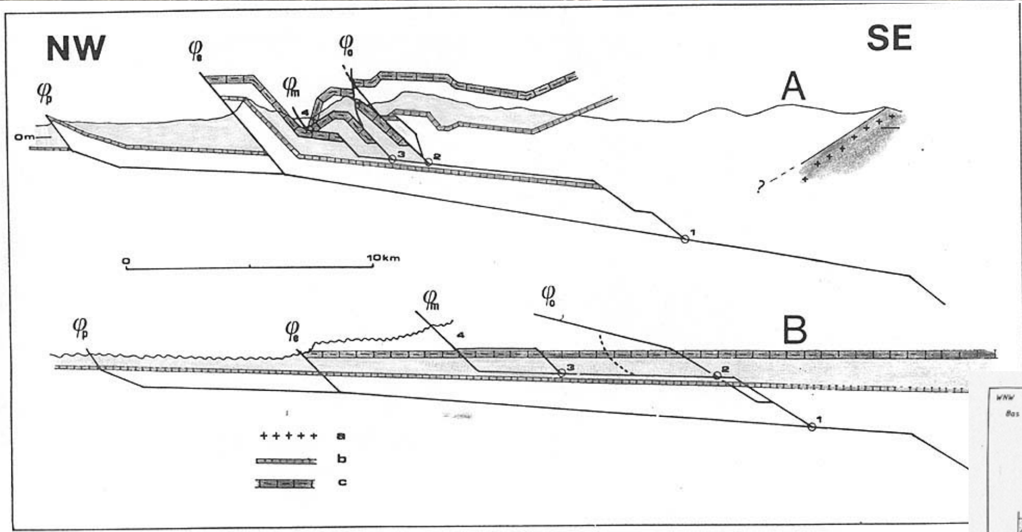






Subalpine thrust belt - good exposure - high relief…





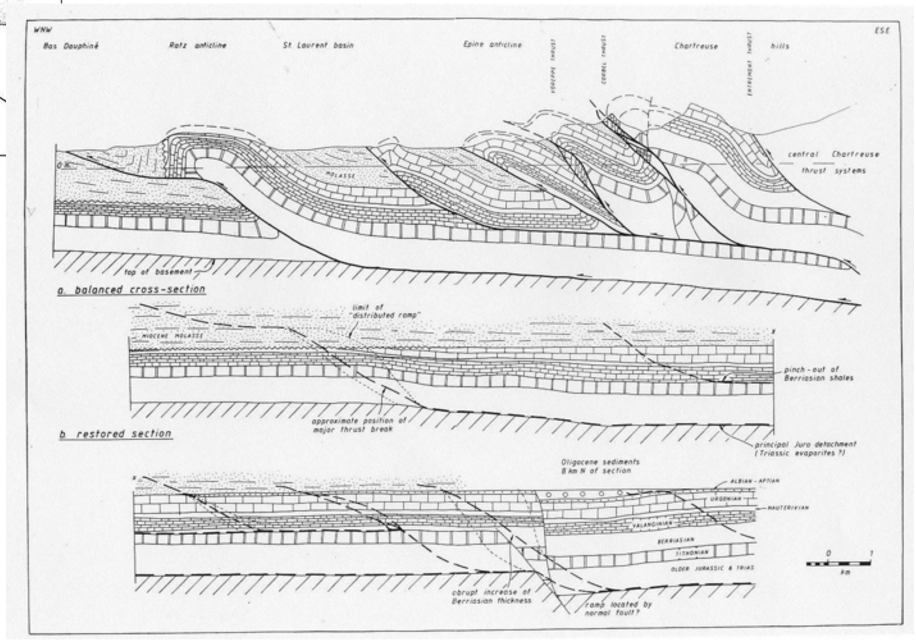
Mugnier et al.

1980s models

Kink-band vs buckles

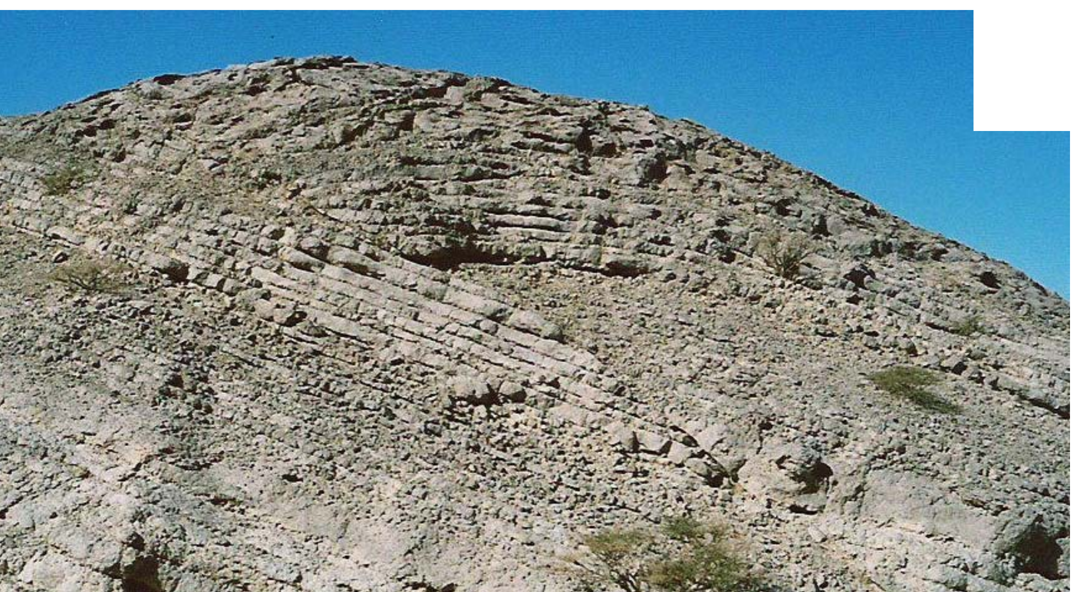
IMPACTS?

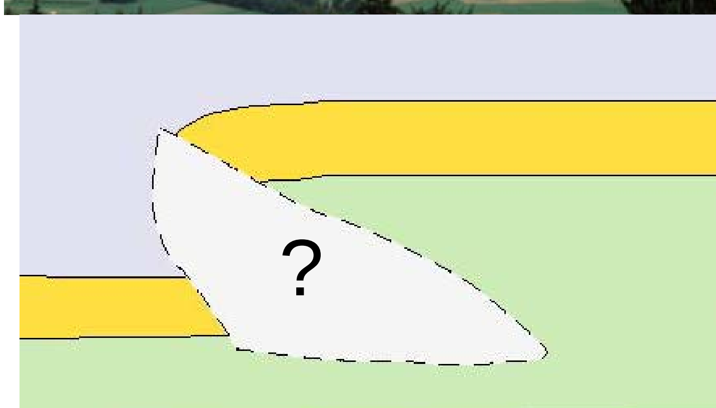
What's the point?
Regional structure - local (e.g. forelimb) - other..?



Butler

Analogues - view the range…

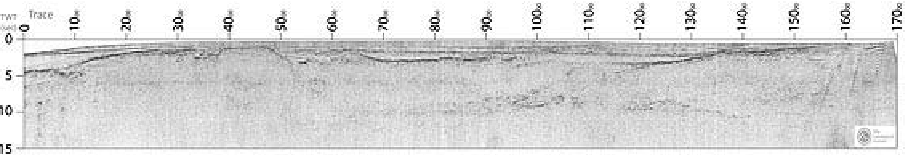


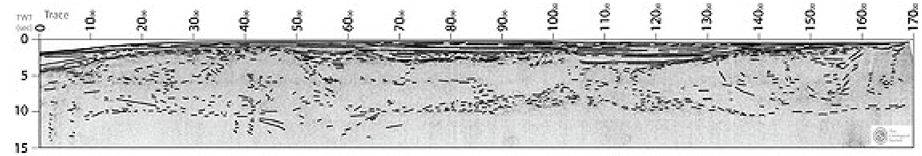


a time out…..

BIRPS NSDP-84: test-bed for continental extensional tectonics…..

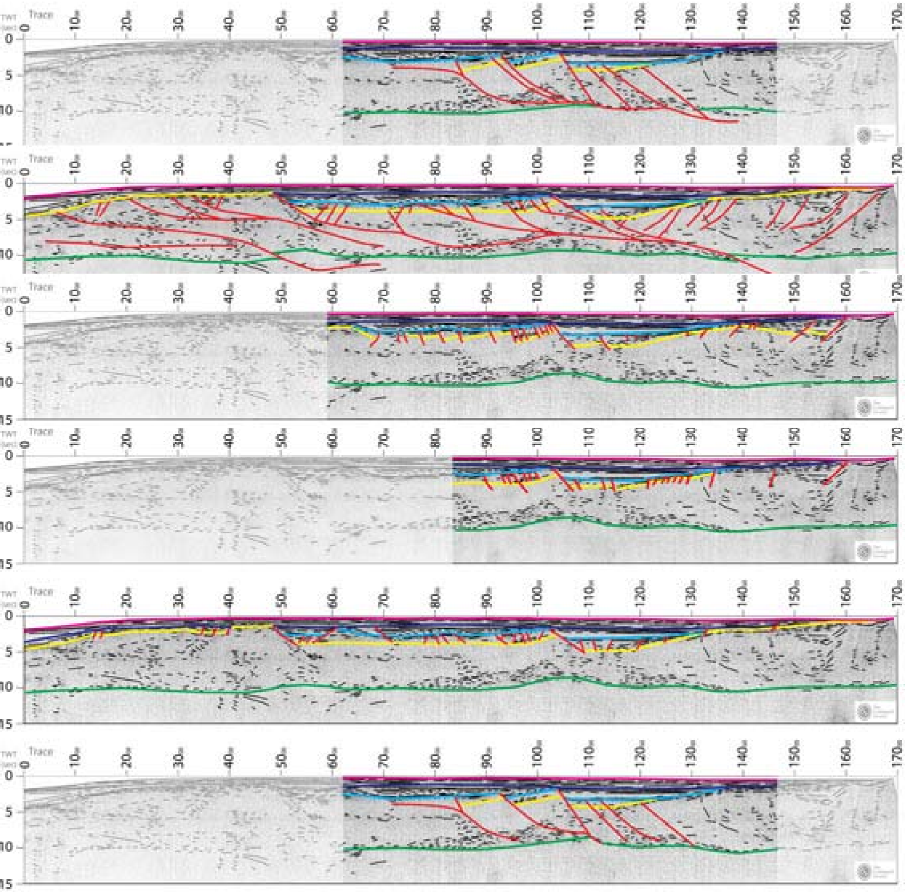
The Virtual Seismic Atlas





Overlain line drawing

Published interpretations



Beach

Gibbs

Marsden et al.

Brun and Tron

Fichler and Hospers

Fossen

Contrasting available existing interpretations… may indicate uncertainty in any one model….

But how do you put the array together?

Known knowns,
Known unknowns,
or
Unknown unknowns!

Project built by Mike Sizer

VSA

Virtual Seismic Atlas

Sharing the geological interpretation of seismic data

The VSA is sponsored by:

VSA Partners:

A new platform…. for analogues…

The Virtual Seismic Atlas

a brief introduction….

BIRPS NSDP 84 -1 (Survey)

BIRPS North Sea Deep Profile - 1 Viking Graben (Regional Project)

Home | Details | Docs & Links | Related

Click here for the full data [jpeg, 1.0 MB]

BIRPS North Sea Deep Profile - 1 Viking Graben (Regional Project)

Author: Mike Sizer **Organization:** N/A
Regions: (0) **Scenes:** (0) **Interpretations:** (7)

This section is a deep profile form the Northern North Sea, originally collected by the BIRPS survey in 1984. Several interpretations of this section have been undertaken since 1986 that show an evolution in the thinking of geologists for the development and architecture of normal fault systems. These can be followed through the linked interpretations.

Interpretations related to this Regional Project

(Interpretation) BIRPS North Sea Deep Profile - 1 overlain line drawing

Author: Mike Sizer **Organization:** N/A
Scenes: (0) **Interpretations:** (0)

This section is a deep profile form the Northern North Sea, originally collected by the BIRPS survey in 1984. Several interpretations of this section have been undertaken since 1986 that show an evolution in the thinking of geologists for the development and architecture of normal fault systems. The first part of the interpretation workflow traditionally is to hand-pick prominent, coherent reflections. Here is one model.

(Interpretation) BIRPS North Sea Deep Profile - 1: line drawing alone

Author: Mike Sizer **Organization:** N/A
Scenes: (0) **Interpretations:** (0)

This section is a deep profile form the Northern North Sea, originally collected by the BIRPS survey in 1984. Several interpretations of this section have been undertaken since 1986 that show an evolution in the thinking of geologists for the development and architecture of normal fault systems. This is the interpretative line drawing of the seismic data - showing prominent reflectors.

(Interpretation) Beach's 1986 interpretation of NSDP84-1

Author: Mike Sizer **Organization:** N/A
Scenes: (0) **Interpretations:** (0)

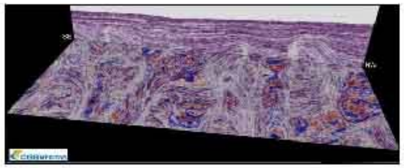
This section shows Beach's interpretation of part of NSDP84-1 that is based on the simple-shear model as proposed by Wernicke (1985). This interpretation is very simple and reflects Beach's broad interpretation of large rotated faulted blocks in a simple hanging-wall/footwall model. The shaded area represents a major extensional shear zone passing upwards from the mantle in the east to the middle crust in the west. Major eastward-dipping extension faults, affecting the hanging-wall of the shear zone, are shown as dotted lines. The base of the crust is shown as a dashed line; the wavy line, drawn as a boundary to areas of different seismic character, reveals a large-scale crustal rollover in the hanging-wall. In the eastern portion of the profile the wavy line corresponds approximately to the base of the Devonian, and top of the metamorphic basement. See: BEACH, A. 1986. A Deep Seismic Reflection Profile across the Northern North Sea. Nature, 232, 53-55. (link to online article - see links section.

(Interpretation) Brun & Tron's 1993 interpretation of NSDP84-1

Author: Mike Sizer **Organization:** N/A
Scenes: (0) **Interpretations:** (0)

Brun and Tron's interpretation of deep seismic reflection profile NSDP84-1 in the Northern North Sea provides a good example of the cumulative developments of the pure-shear model from before the early nineties. The normal faults are planar and only developed in the upper part of the crust.

3D fold in Deep Water Niger delta (Regional Project)



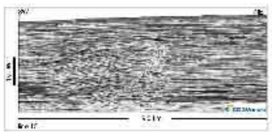
Click here for the full data [jpeg, 1.4 MB]

3D fold in Deep Water Niger delta (Regional Project)

Author: Estelle Mortimer, Rob Butler **Organization:** N/A
Regions: (0) **Scenes:** (7) **Interpretations:** (1)

This project acts a hub for exploring the 3D structure of a fold-thrust structure in deep water, western Niger delta. In the "docs and links" there is a pdf with 48 serial sections through the fold. The associated scene projects consist of 7 triptychs, each of which contains a clean version of the seismic, an interpreted version and an annotated interpretation. These are a subset of the serial sections in the pdf.

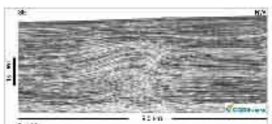
Scenes related to this Regional Project



(Scene) DW Niger delta fold - profile N13

Author: Rob Butler **Organization:** N/A
Scenes: (0) **Interpretations:** (2)

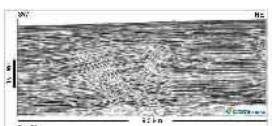
Back-thrust structure - with associated fold that verges up regional slope.



(Scene) DW Niger delta fold - profile N18

Author: Rob Butler **Organization:** N/A
Scenes: (0) **Interpretations:** (2)

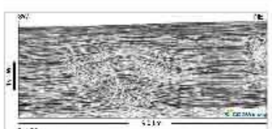
Nearing the transfer zone along the anticline as the structure changes from a back-thrust (in NE) to a fore-thrust (in the SW). Both vergences are evident at depth - along the Agbada/Akata transition.



(Scene) DW Niger delta fold - profile N20

Author: Rob Butler **Organization:** N/A
Scenes: (0) **Interpretations:** (2)

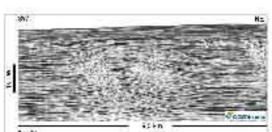
Triangle zone/pop-up structure in the deep water Western Niger Delta. Both thrusts pass upwards into trishear zones.



(Scene) DW Niger delta fold - profile N29

Author: Rob Butler **Organization:** N/A
Scenes: (0) **Interpretations:** (2)

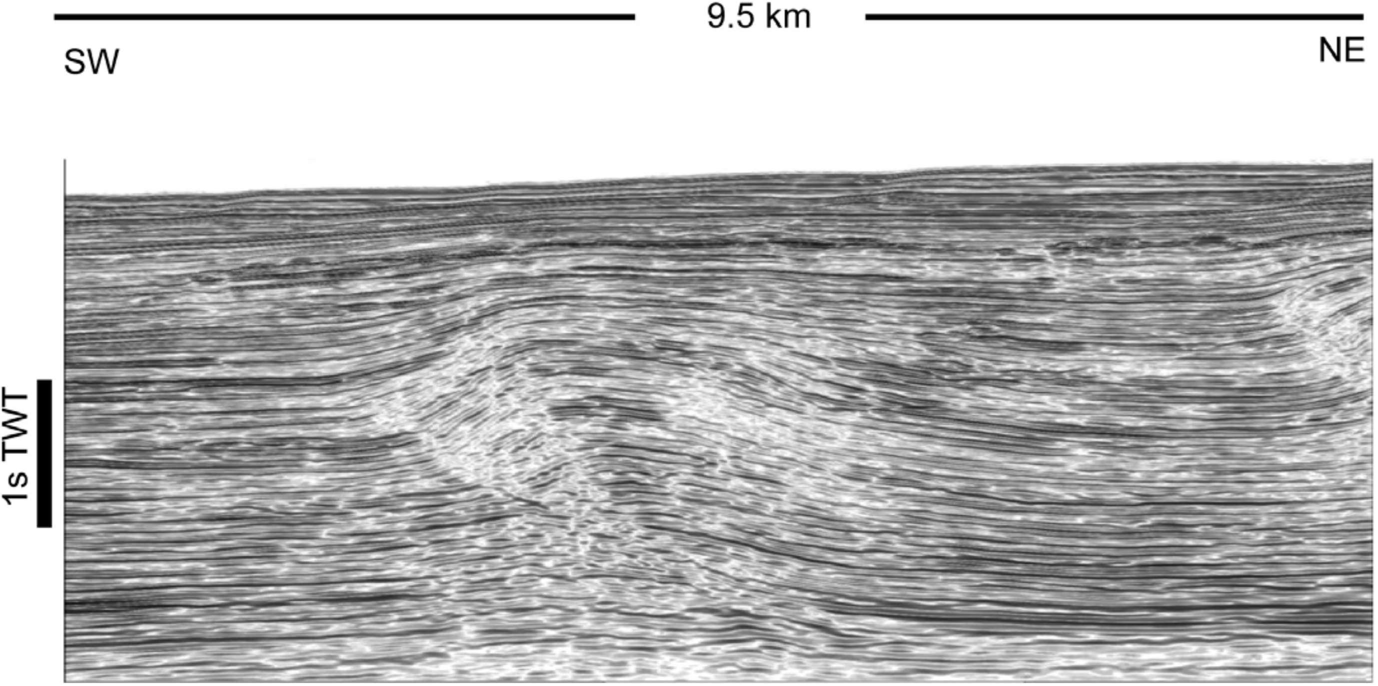
Fore-thrust structure from the deep water Western Niger Delta.



(Scene) DW Niger delta fold - profile N34

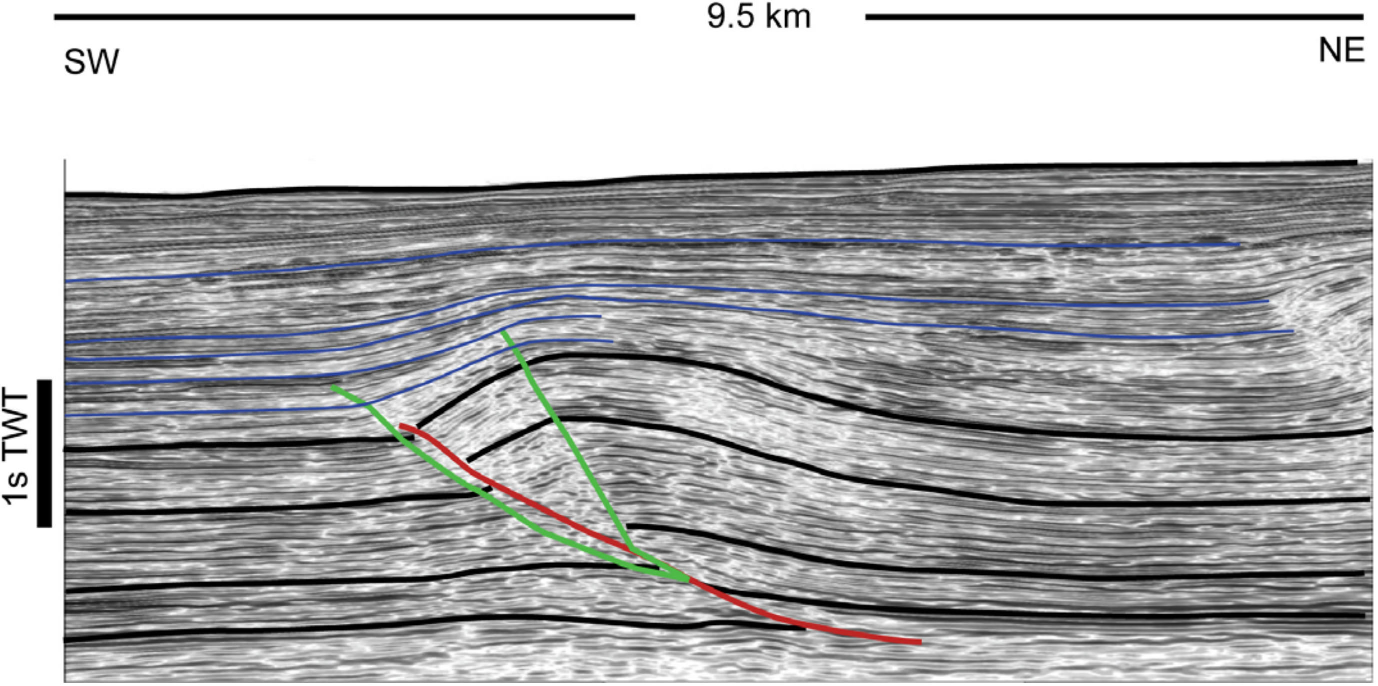
Author: Rob Butler **Organization:** N/A
Scenes: (0) **Interpretations:** (2)

Fore-thrust structure in deep water Western Niger delta.



The Virtual Seismic Atlas

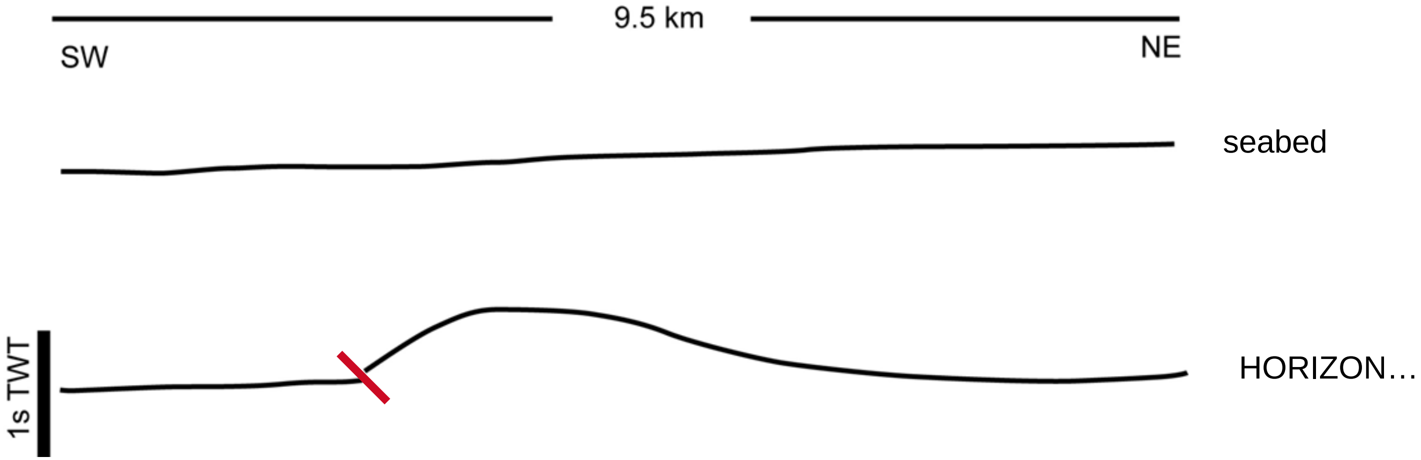
CGGVeritas



The Virtual Seismic Atlas

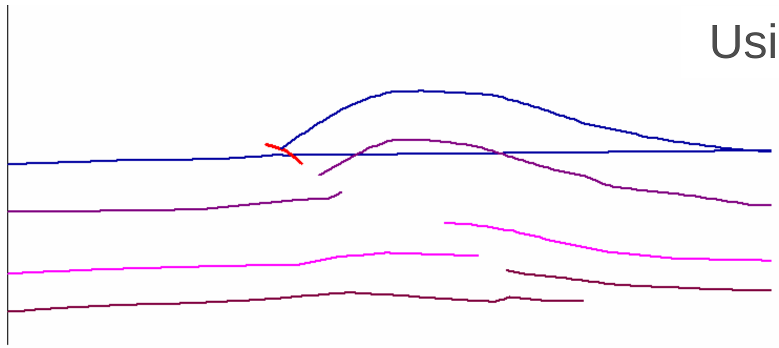
Midland Valley

2DMove
used for restoration

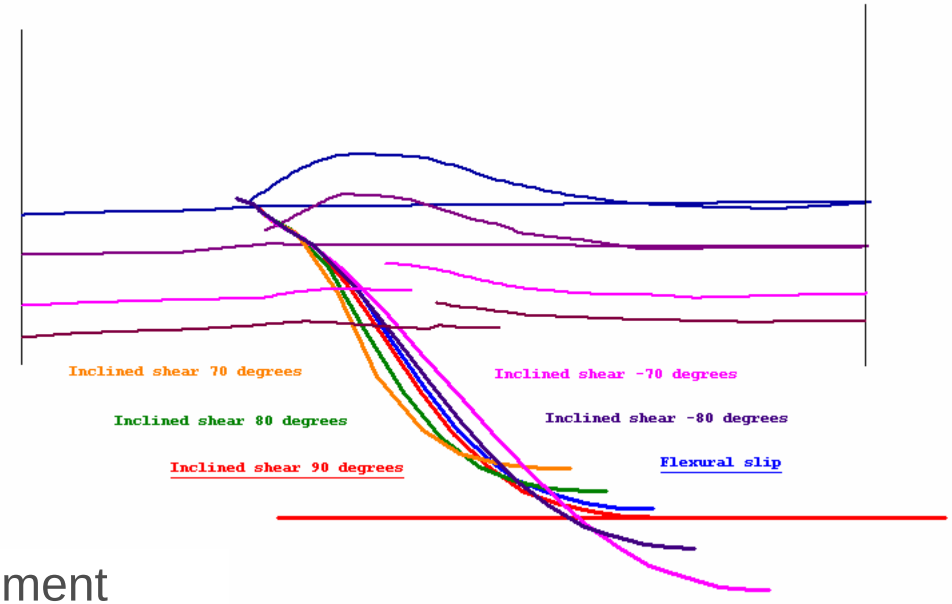


Scenario modeling

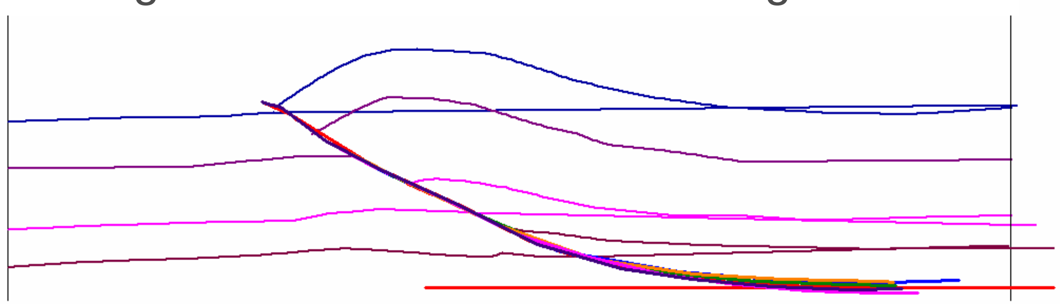
Predicting Fault shape and geometry



Using the top two beds and a small fault segment



Using all beds and a small fault segment

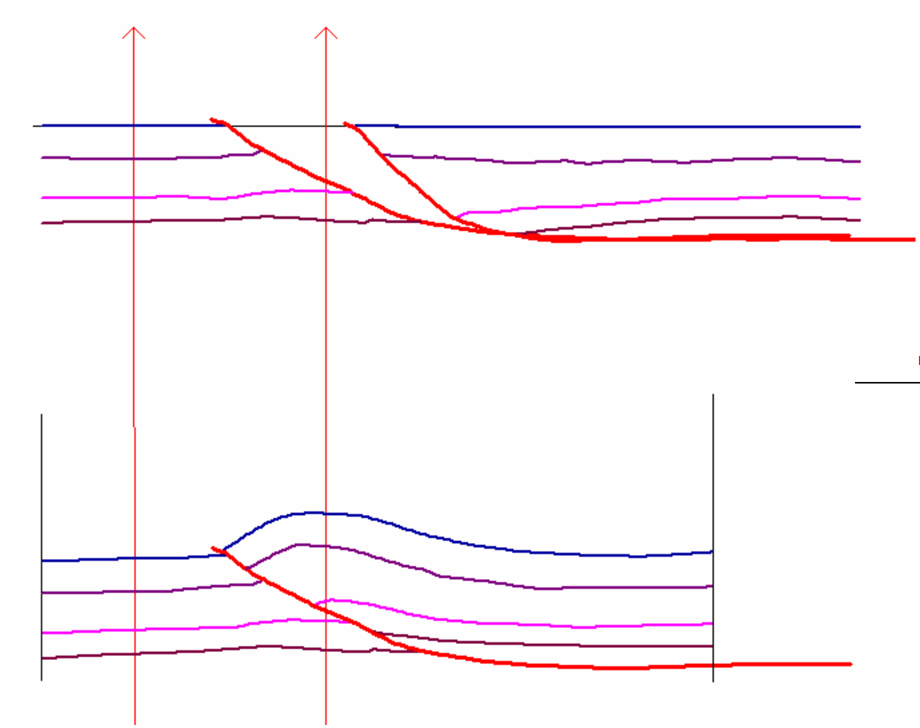


NB : Changing the algorithm has a minimal effect

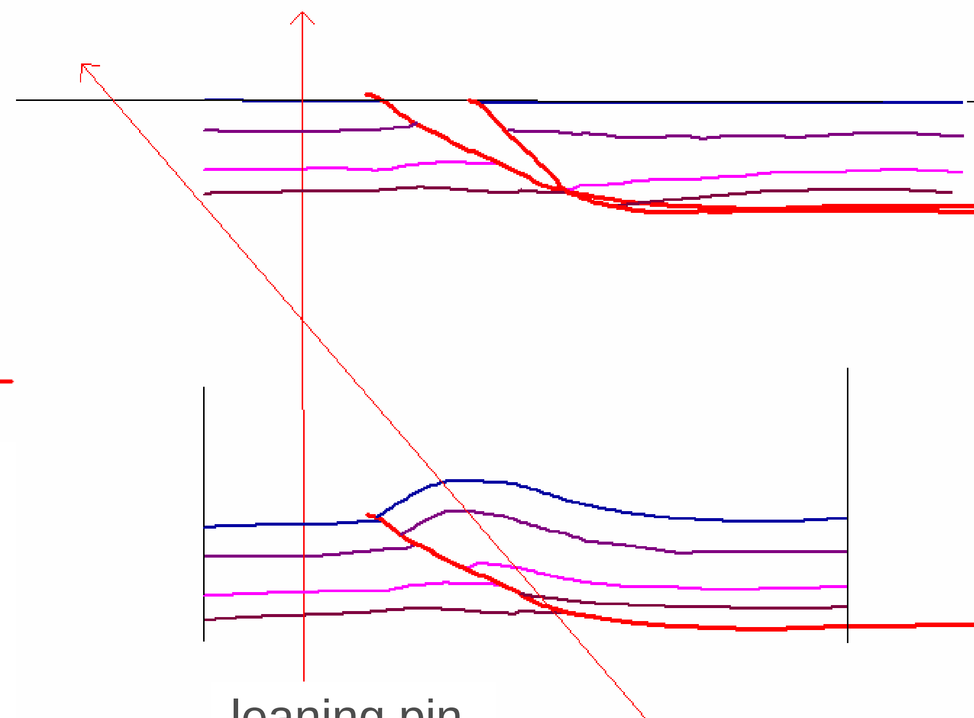
Midland Valley

2DMove

Flexural Slip unfold – geometry testing



Straight pin

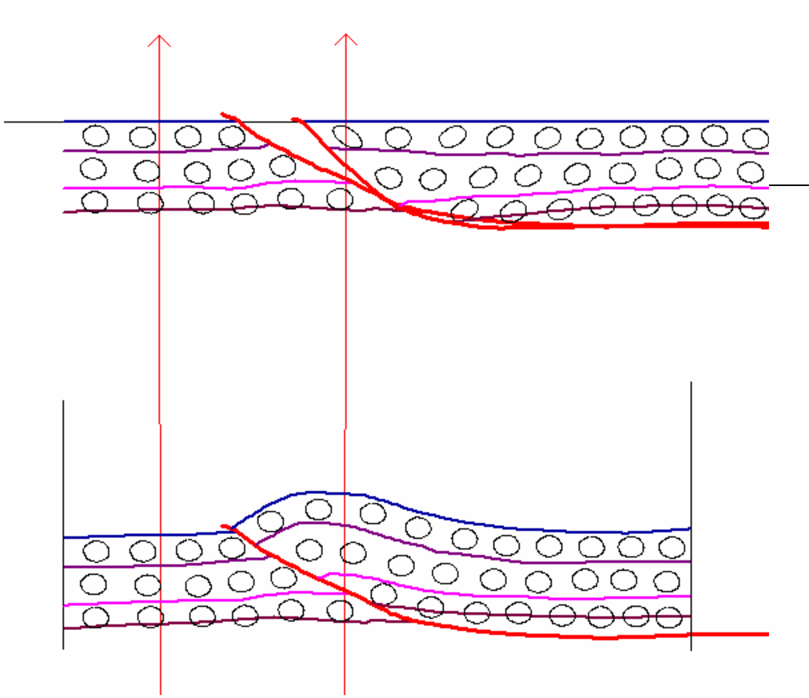


leaning pin

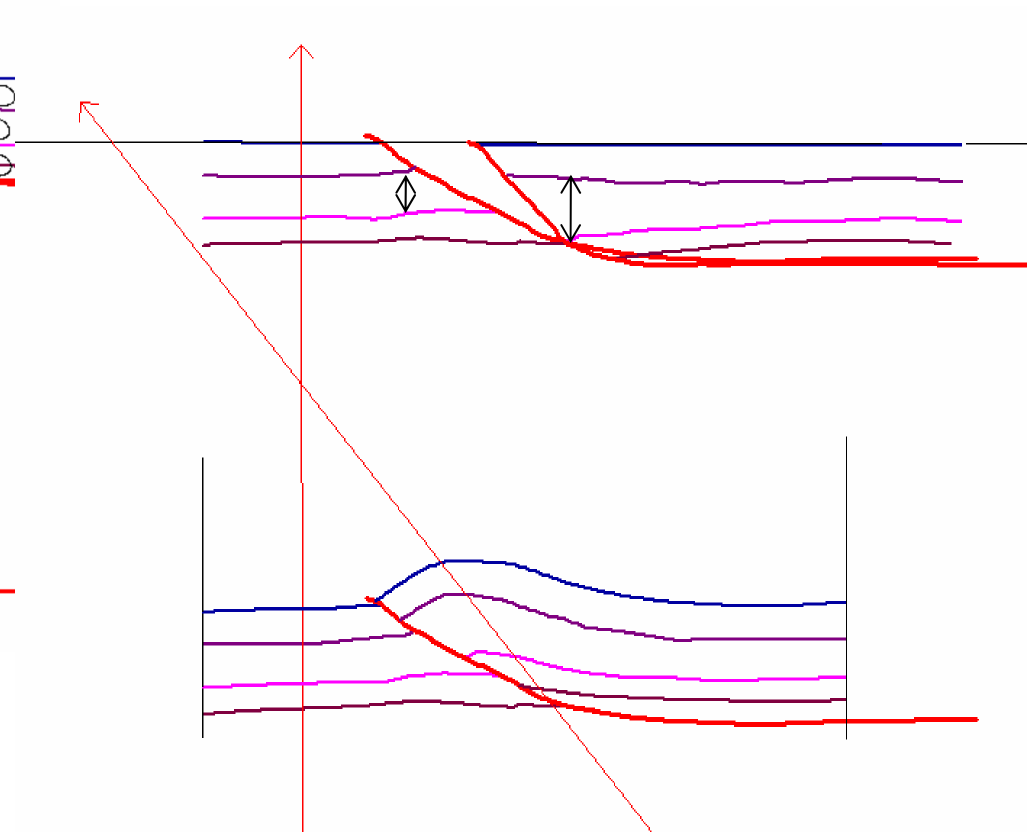
Midland Valley

2DMove

Flexural Slip unfold – geometry testing



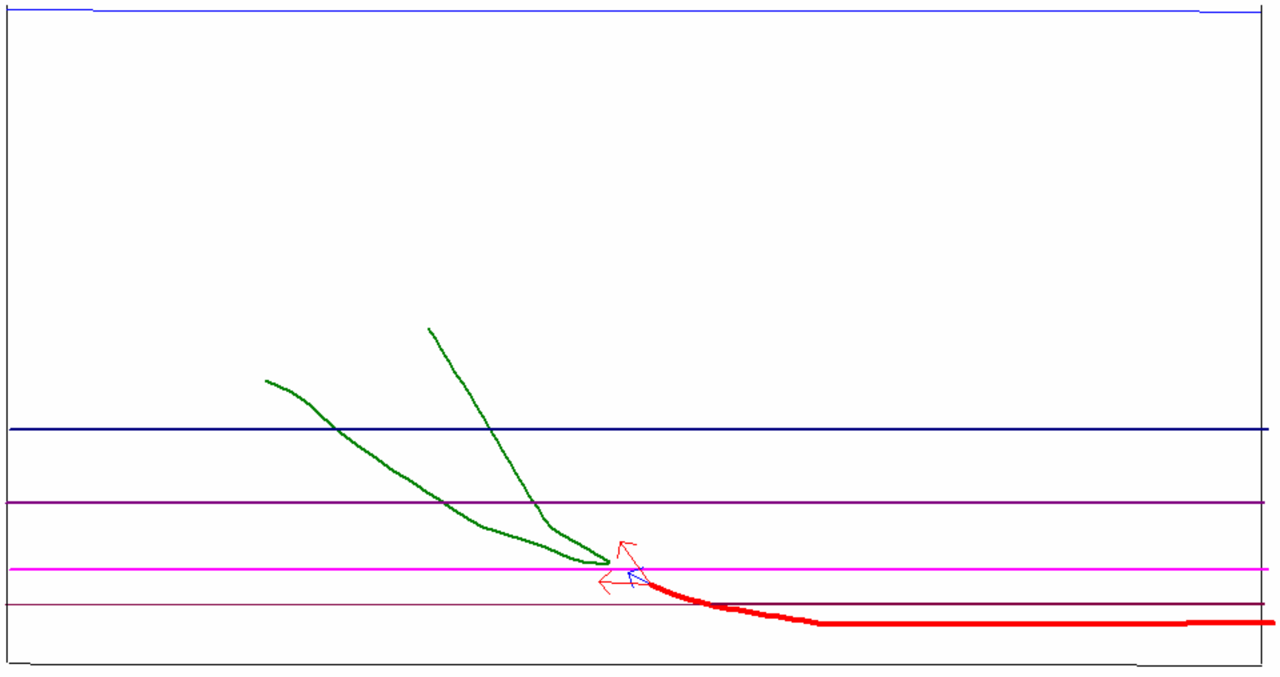
Straight pin –deformation



All tests highlight unlikely thickening in middle package – reinterpretation…

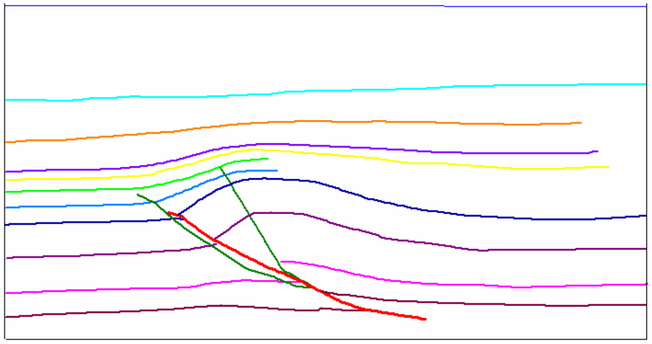
Midland Valley

2DMove



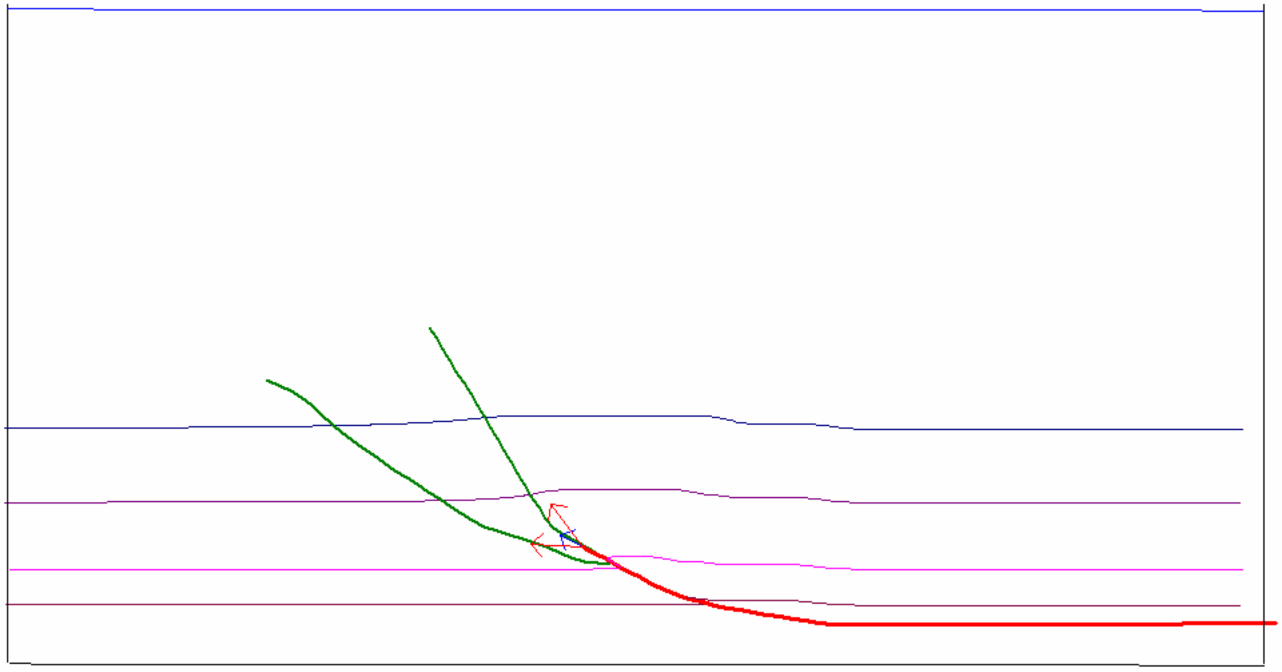
Midland Valley

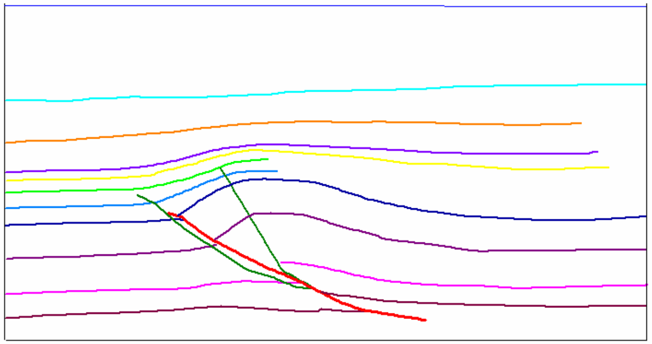
2DMove

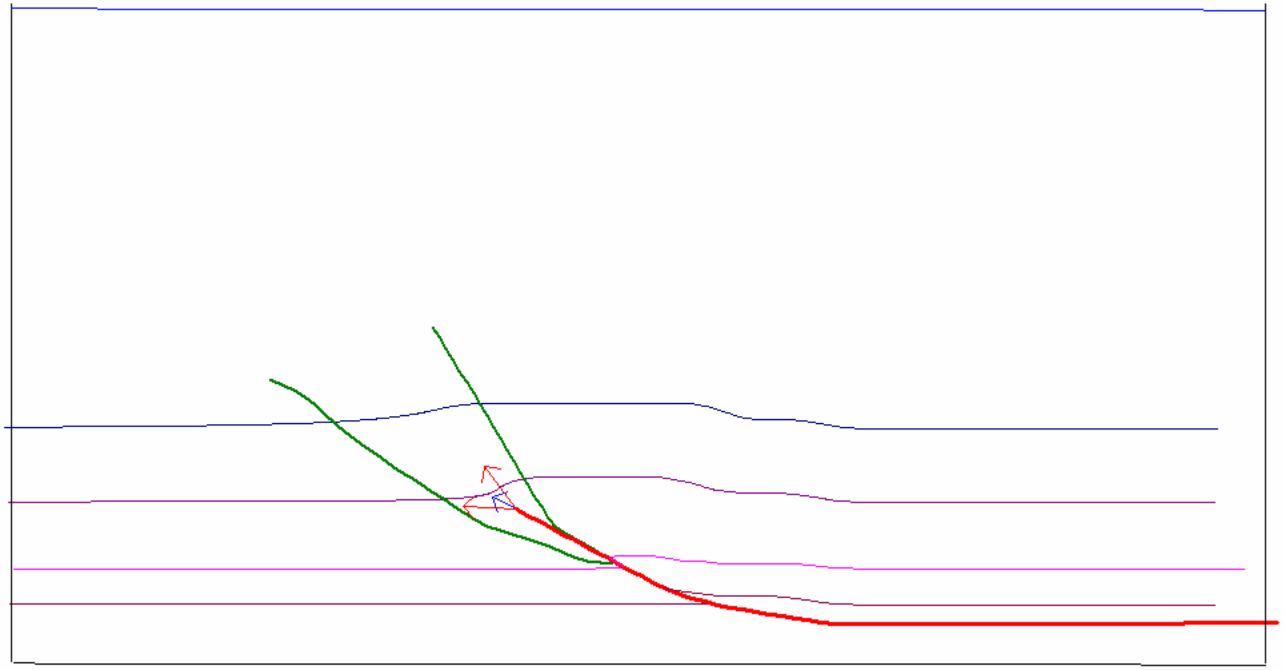


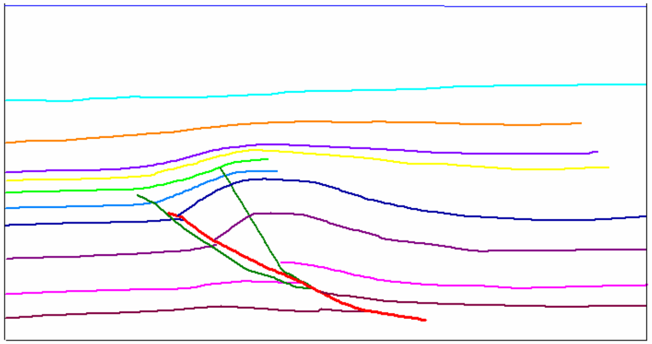
Approach - forward models
Trishear

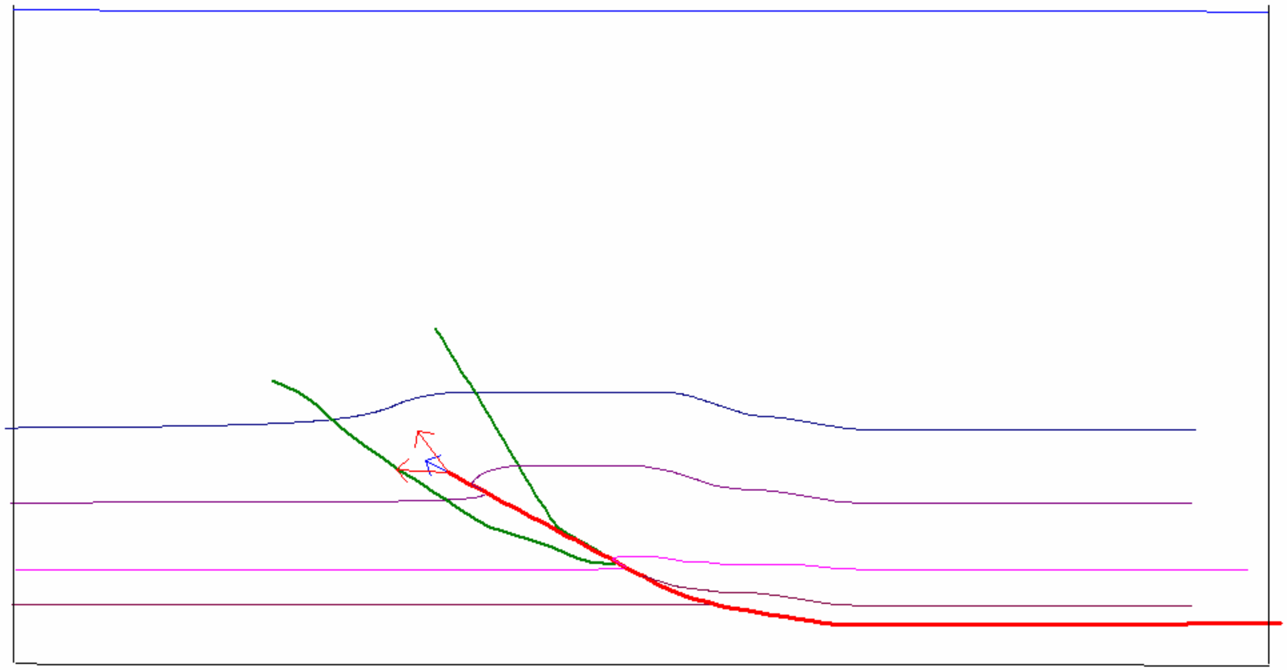
Variables:
Slip/ propagation rate
Trishear aperture

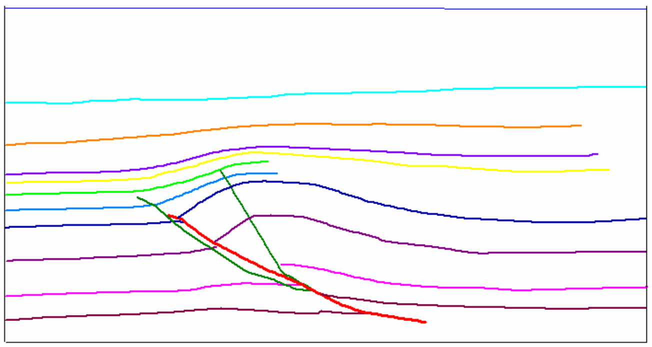


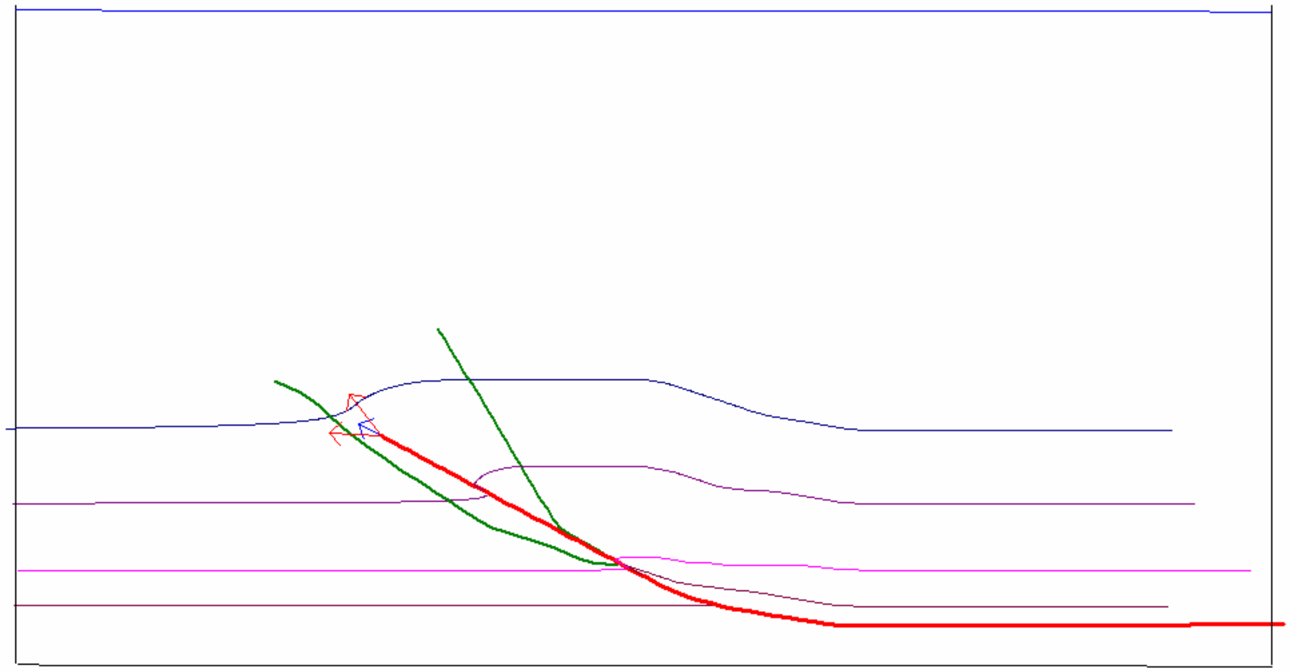


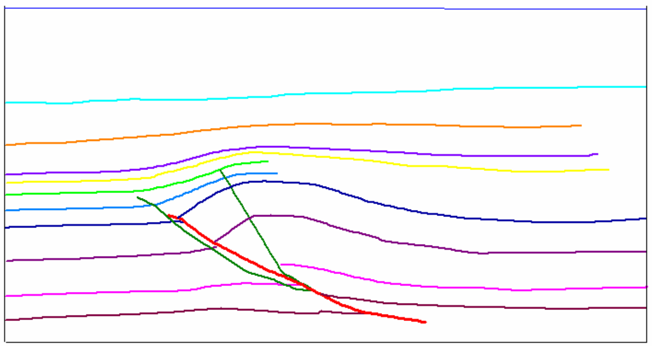


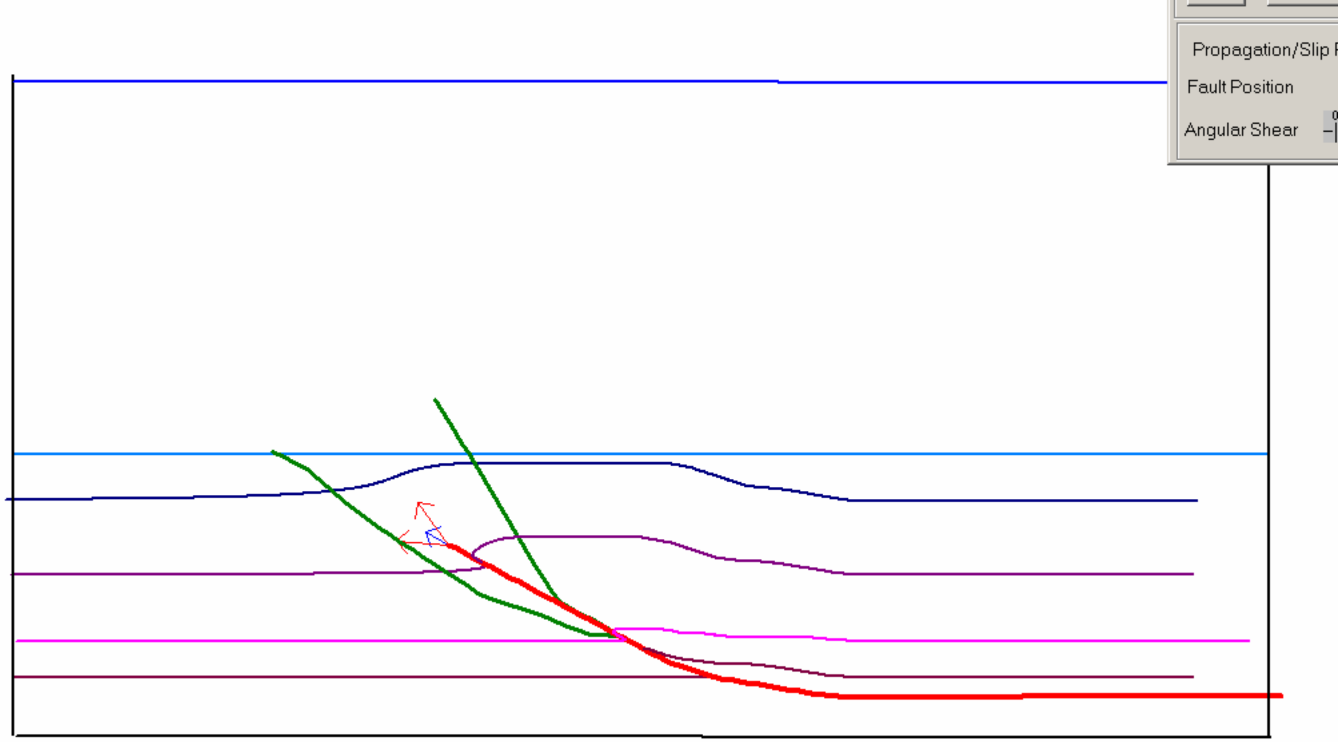


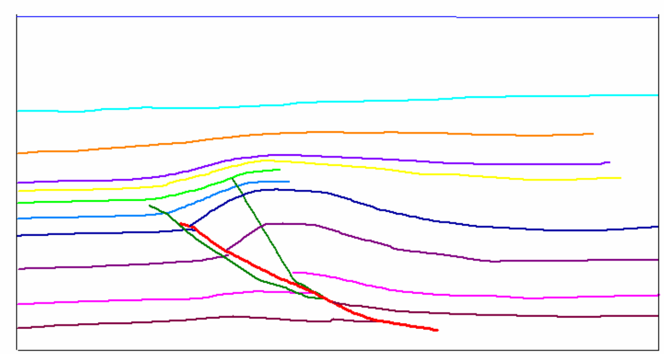


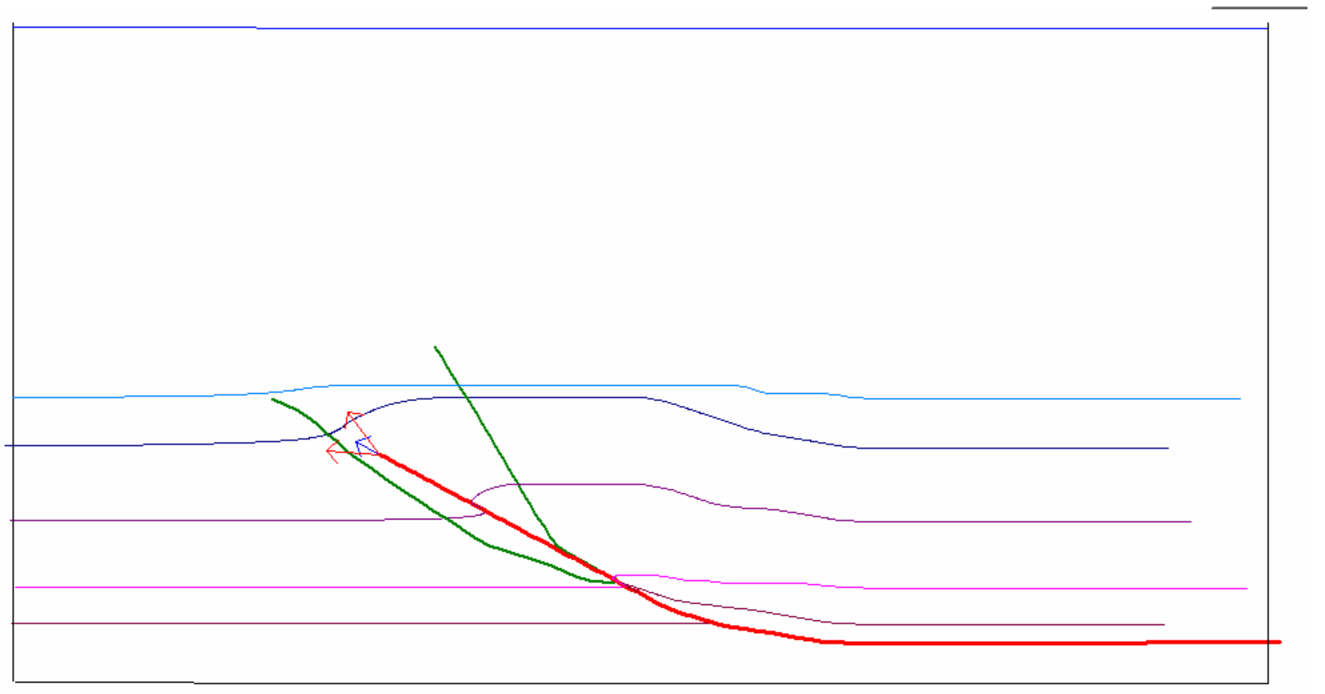




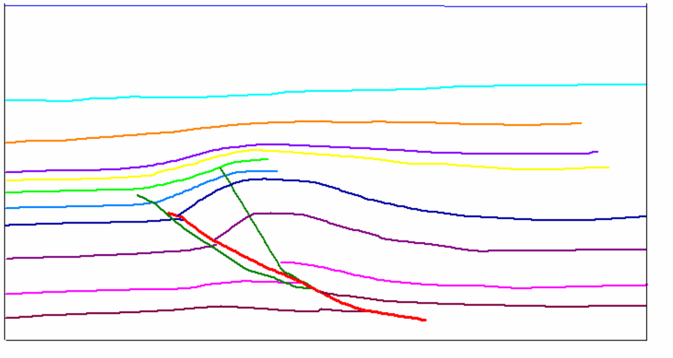


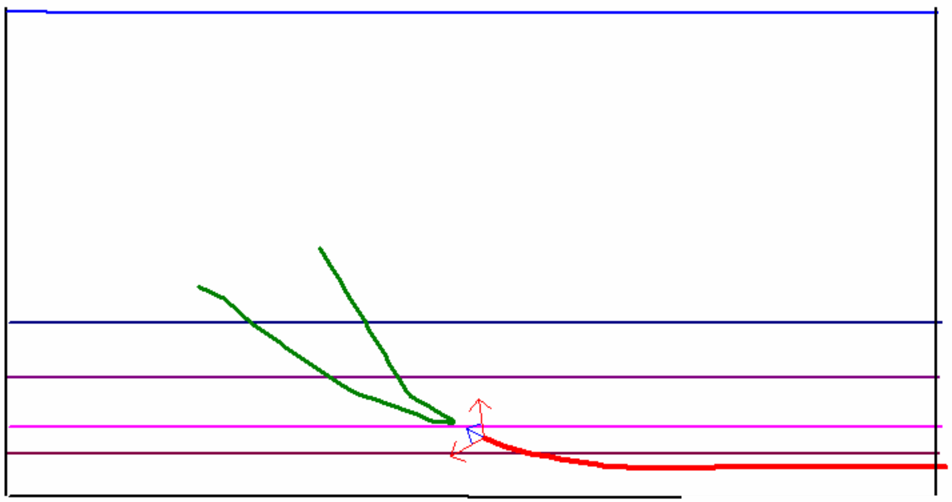

Propagation/Slip
Fault Position
Angular Shear

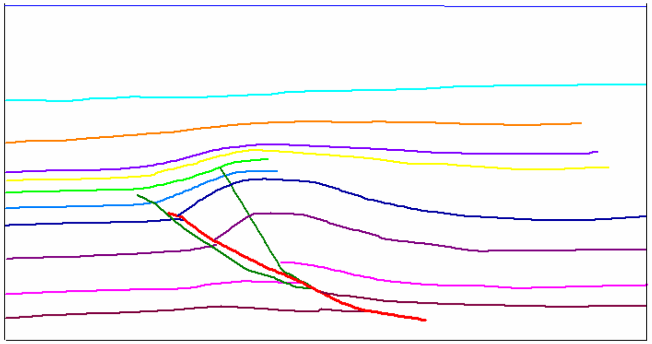


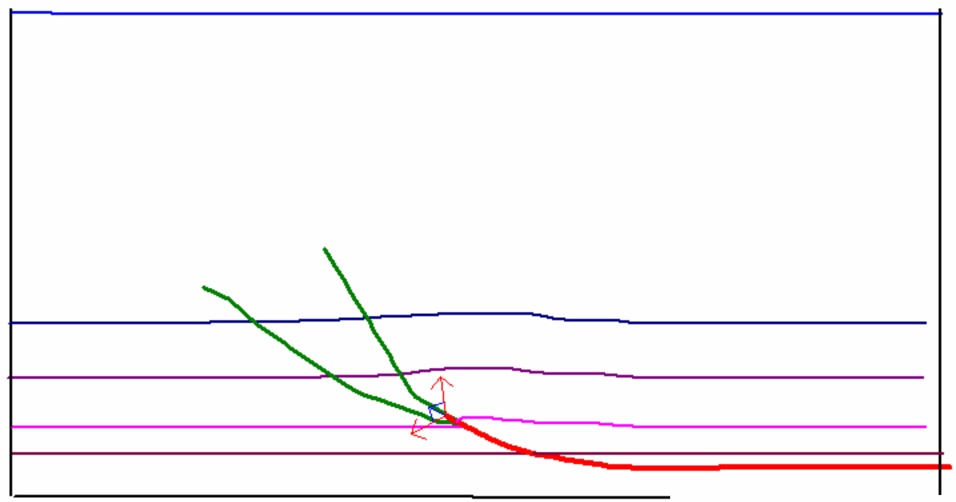


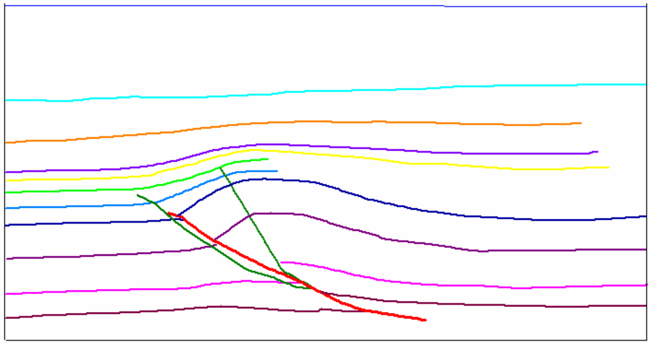
Forelimb not steep enough
Trishear apex 28.1
200m displacement, each step
prop/slip 3
trishear 50 degs

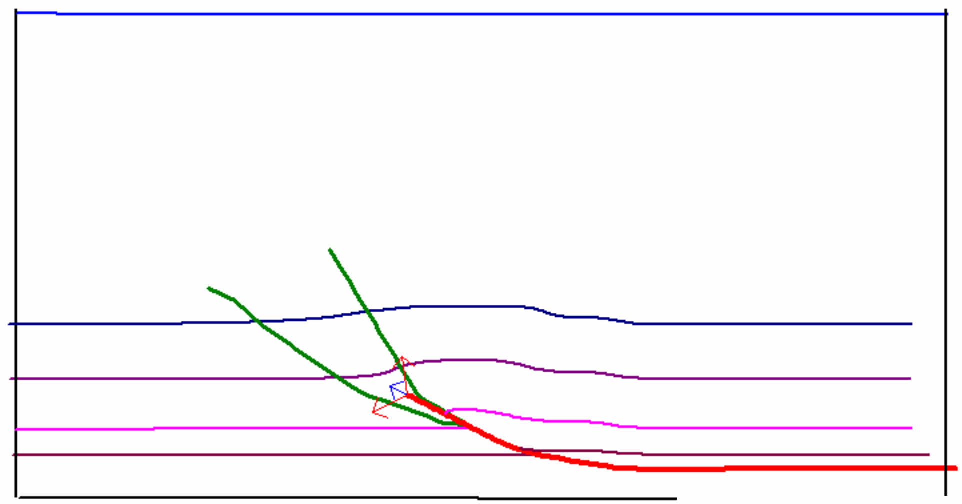


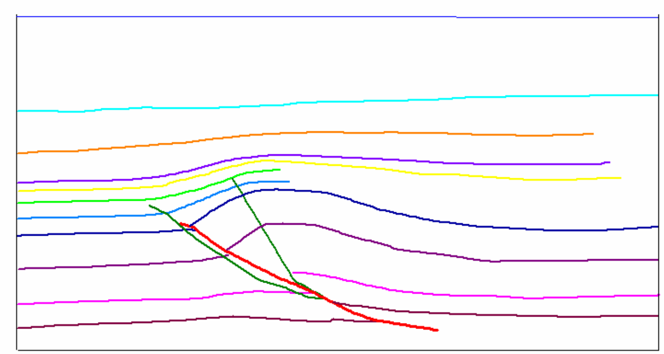


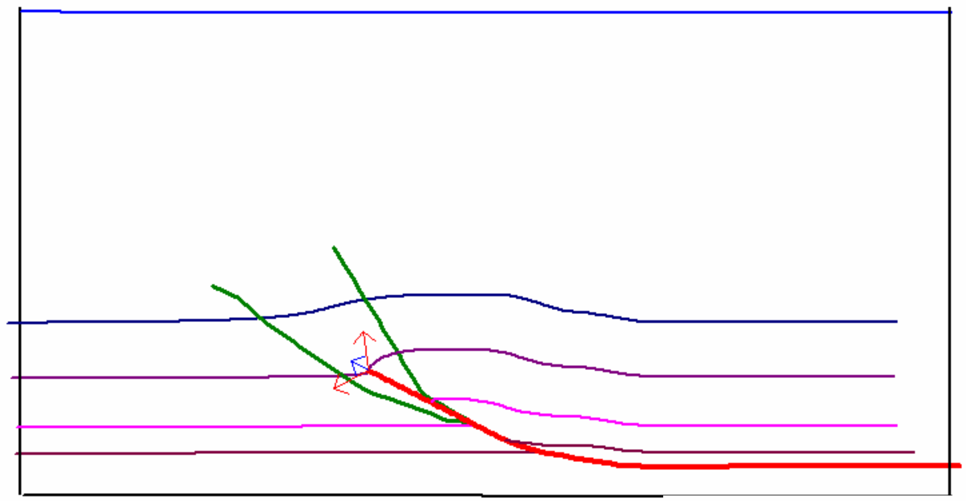


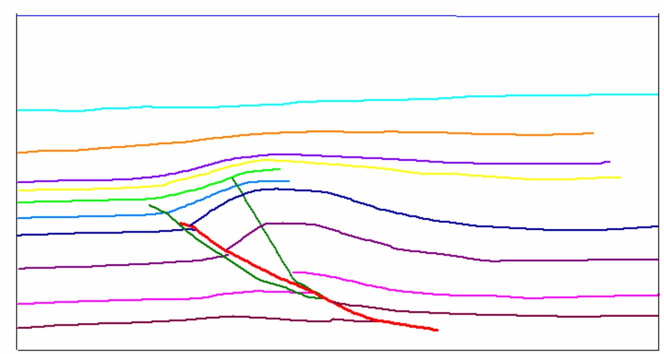


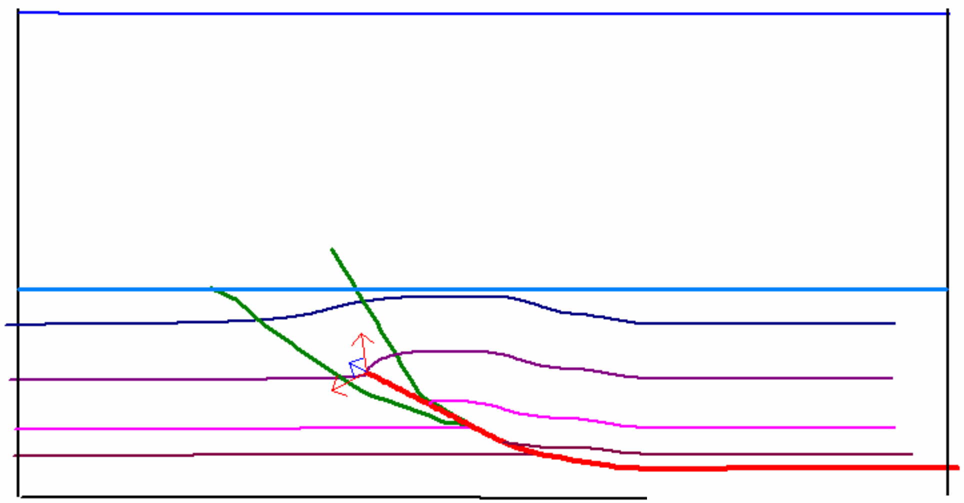


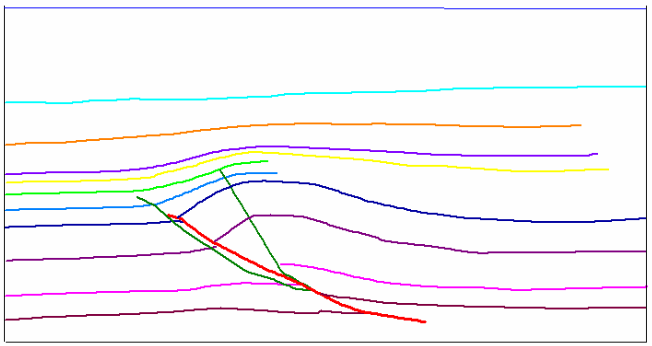


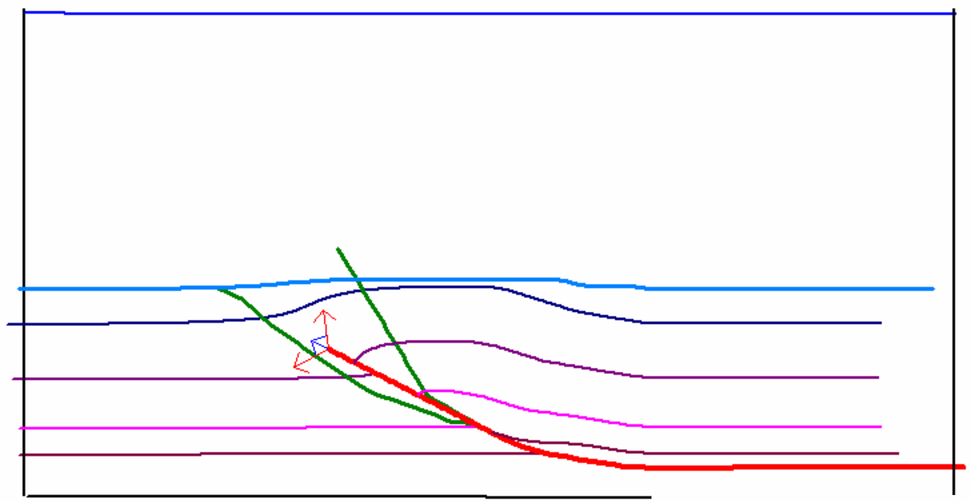


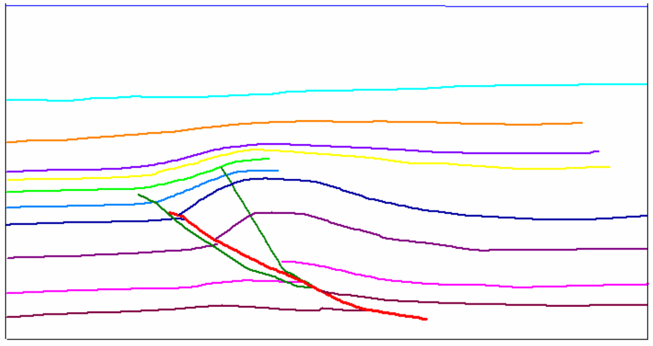


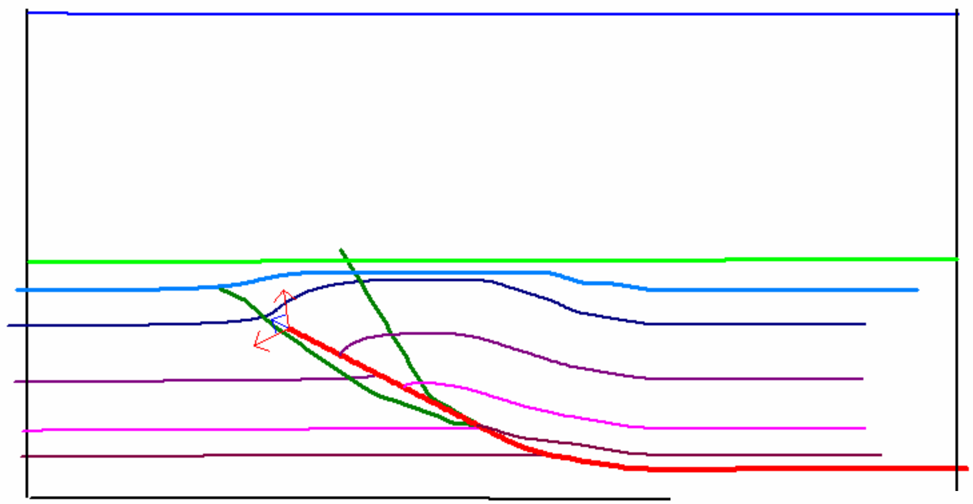


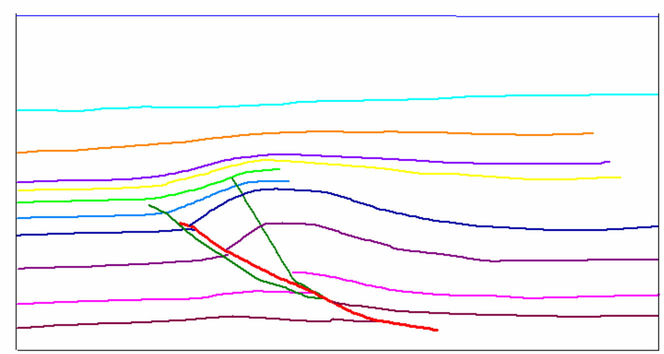


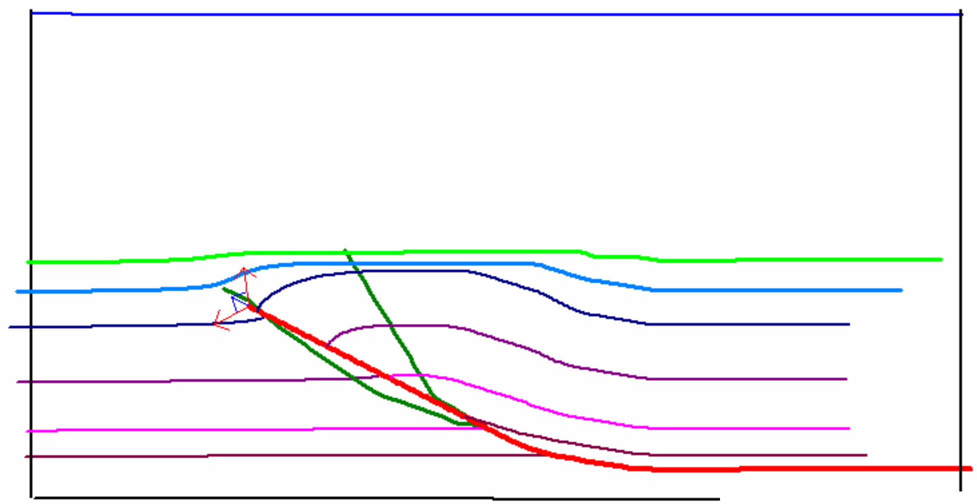


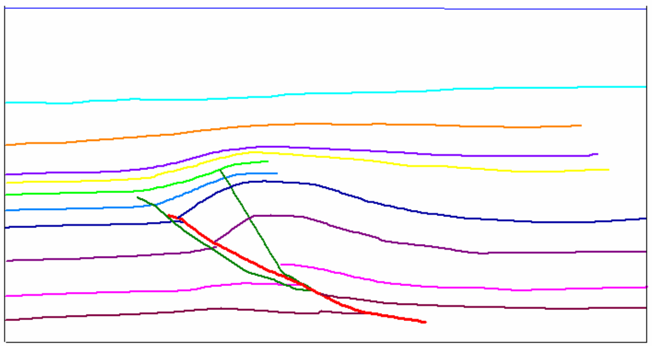


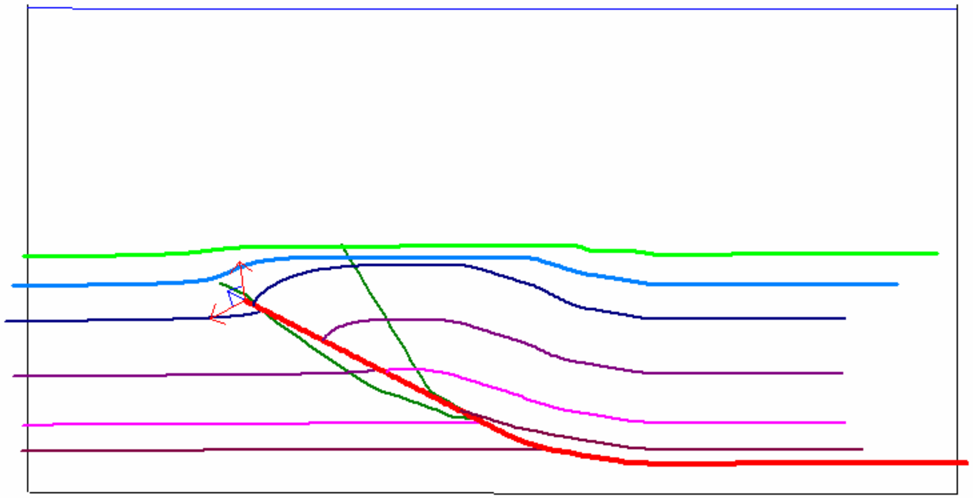




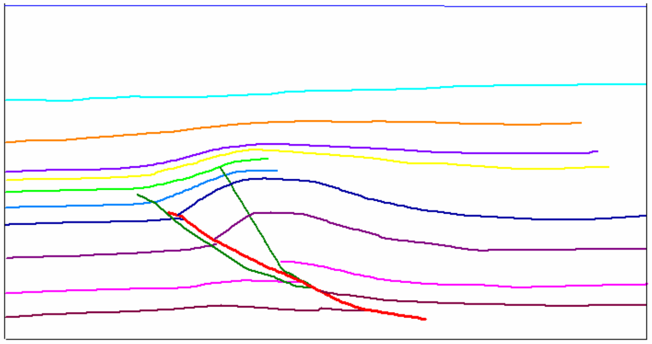




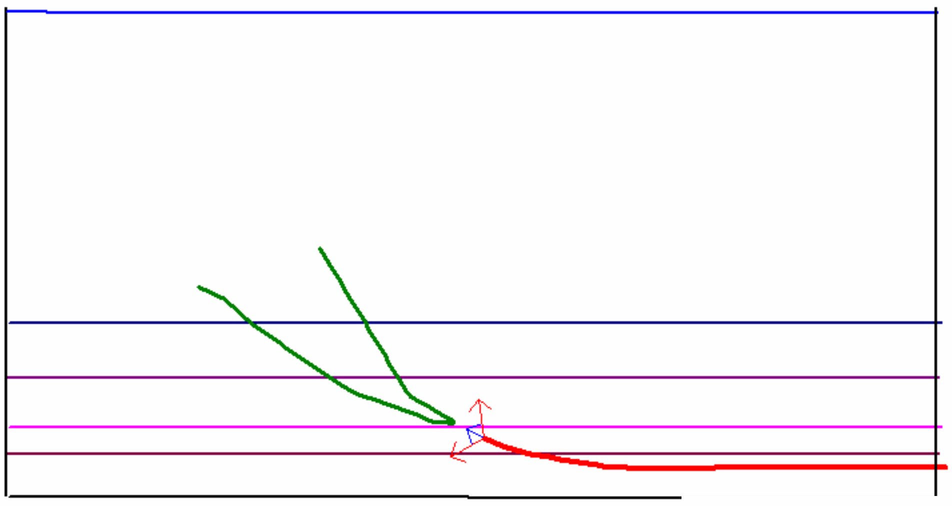


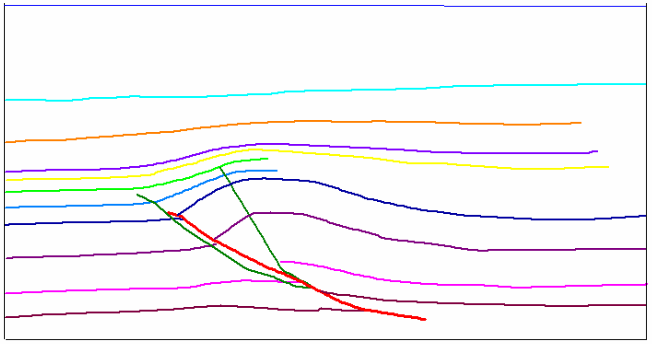


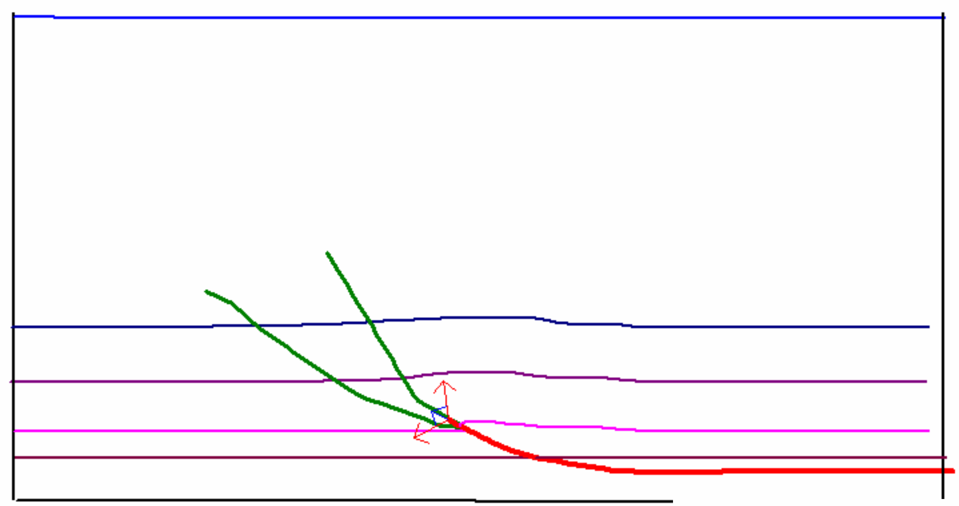
Stratigraphy does not fit -
change depositional model

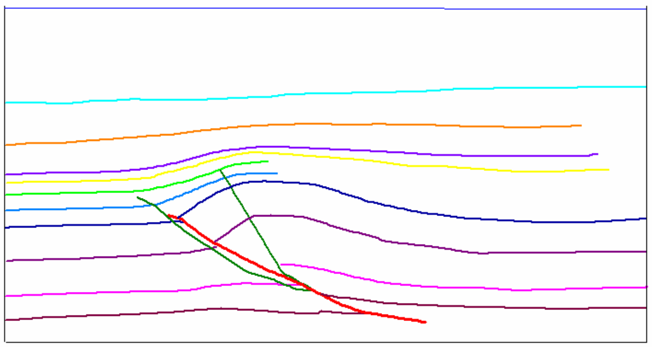


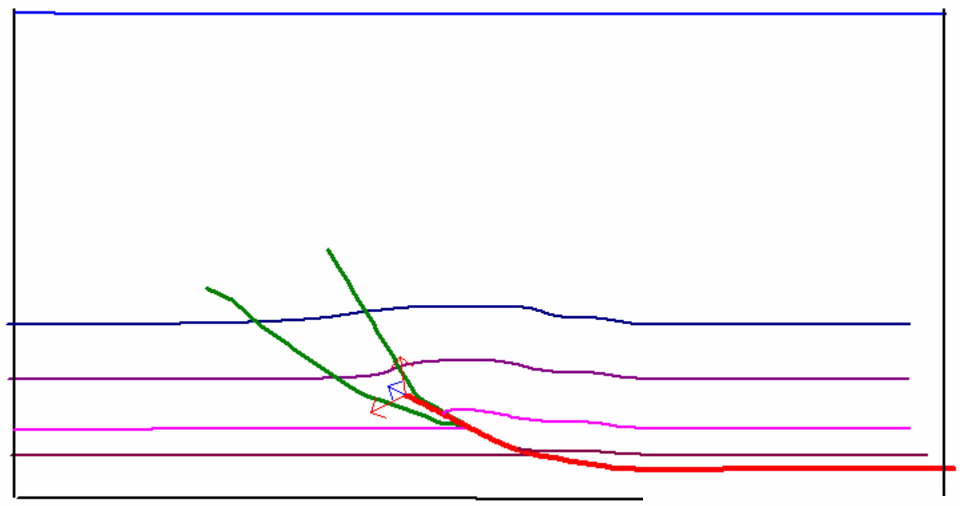
Adding beds earlier

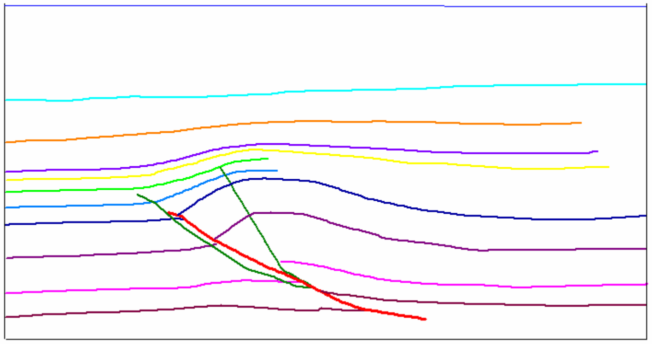


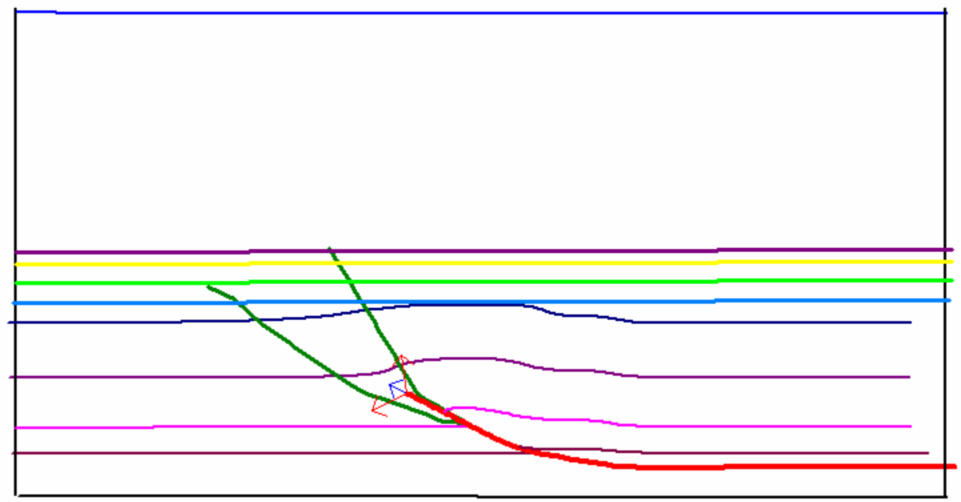


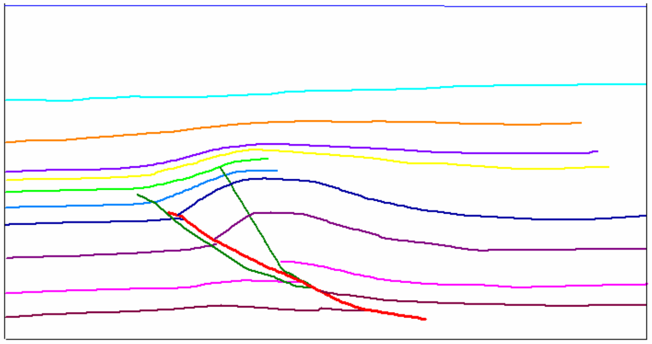


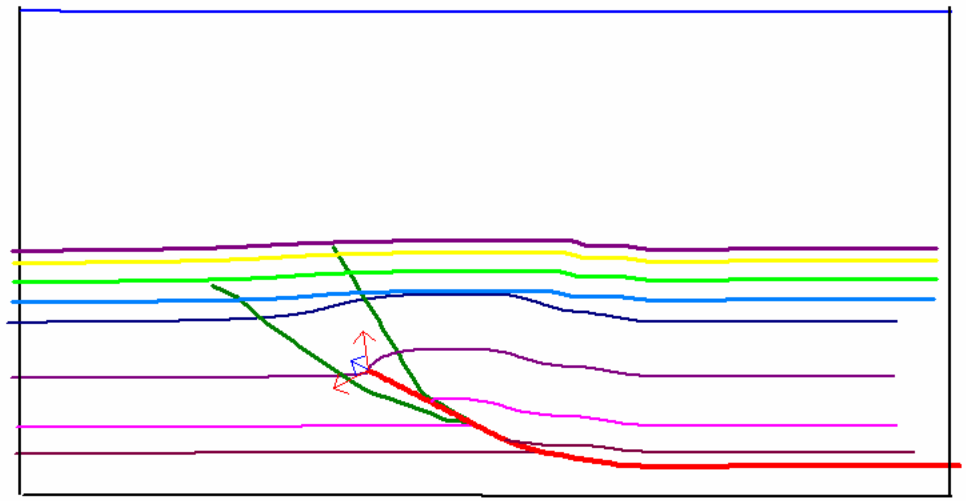


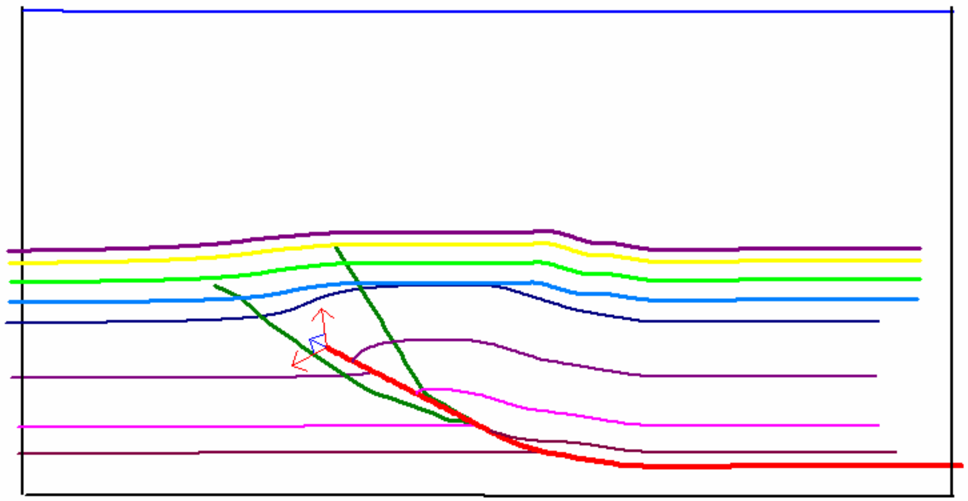


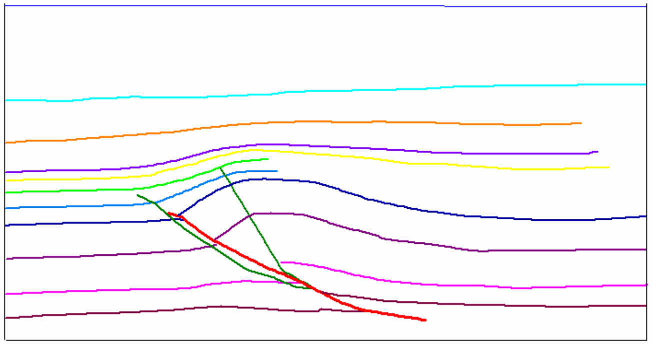


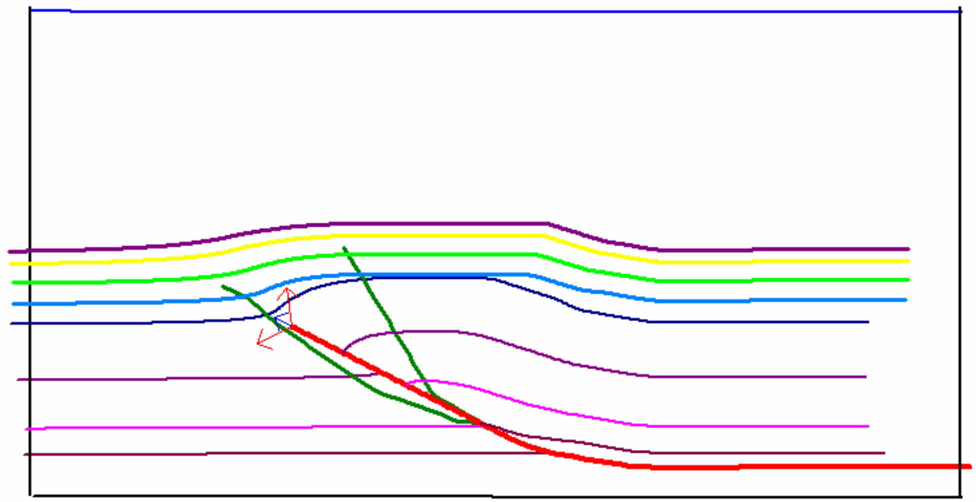


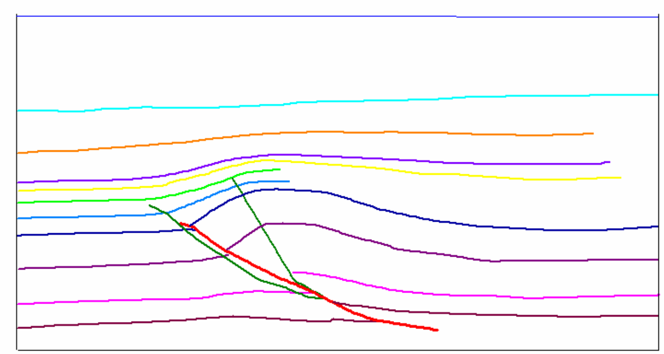


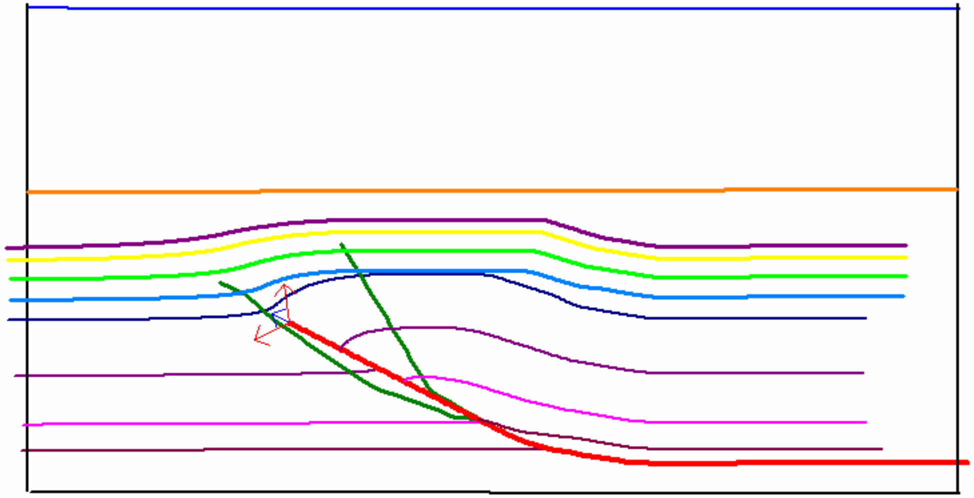


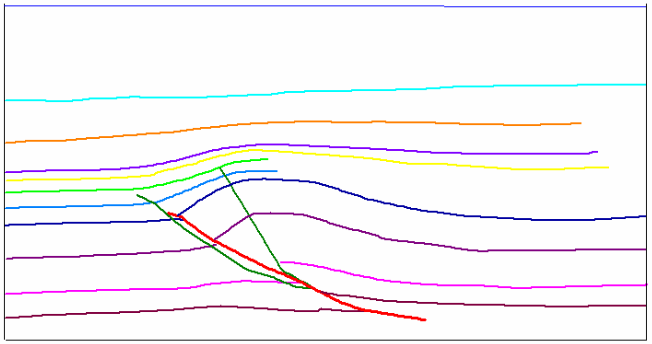


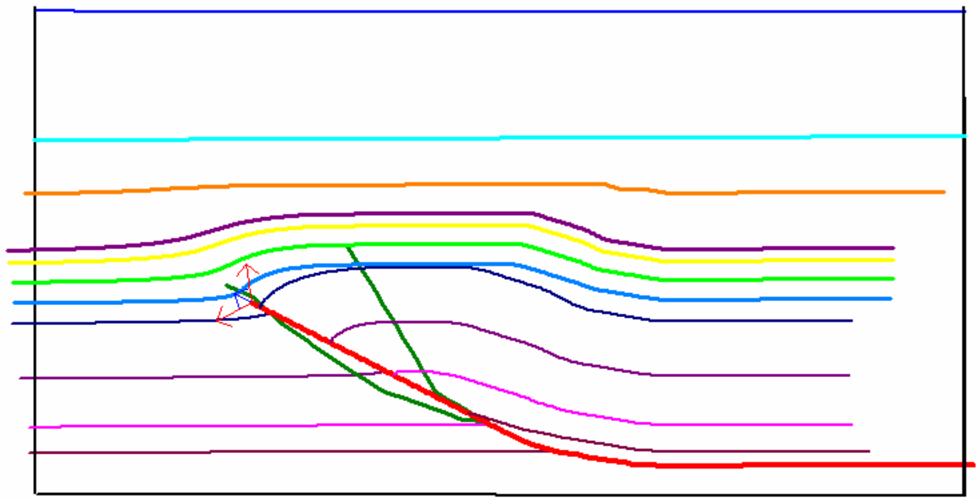




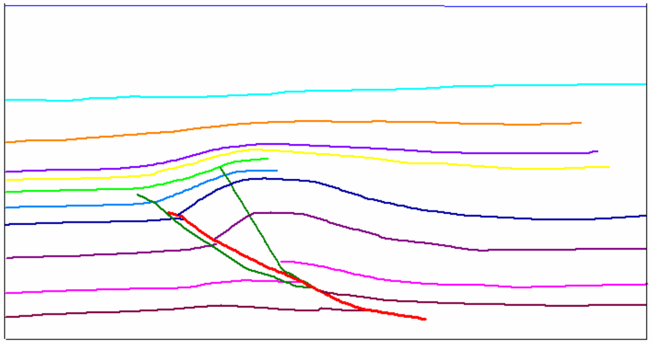


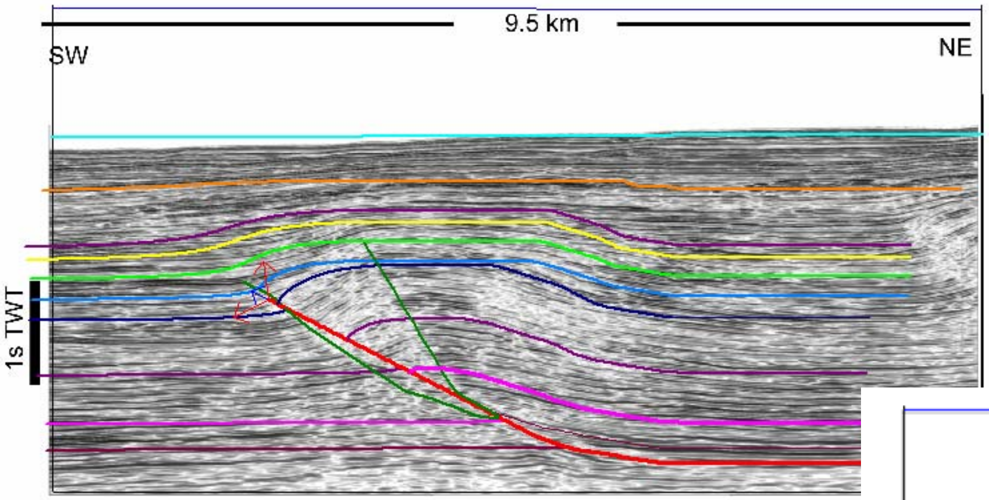


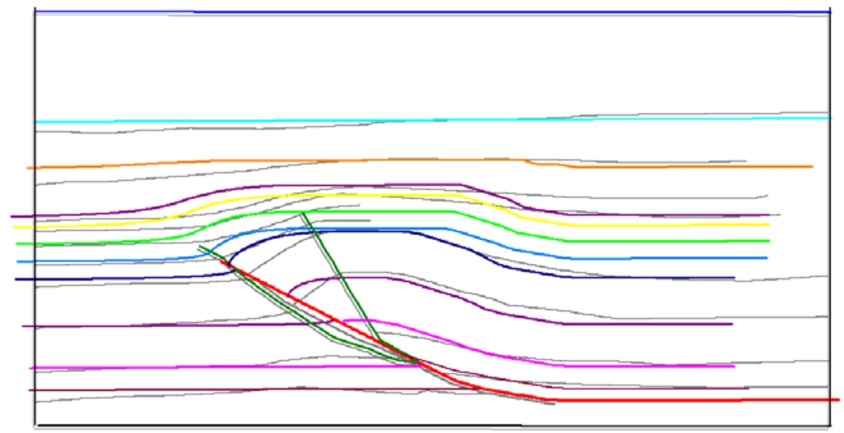




Faster deposition rate (early) fits
the forward model better to interpretation

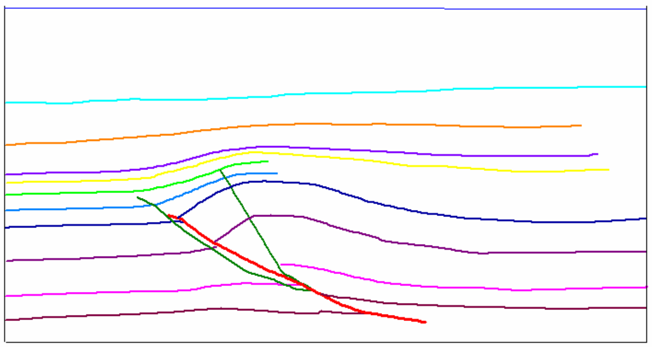


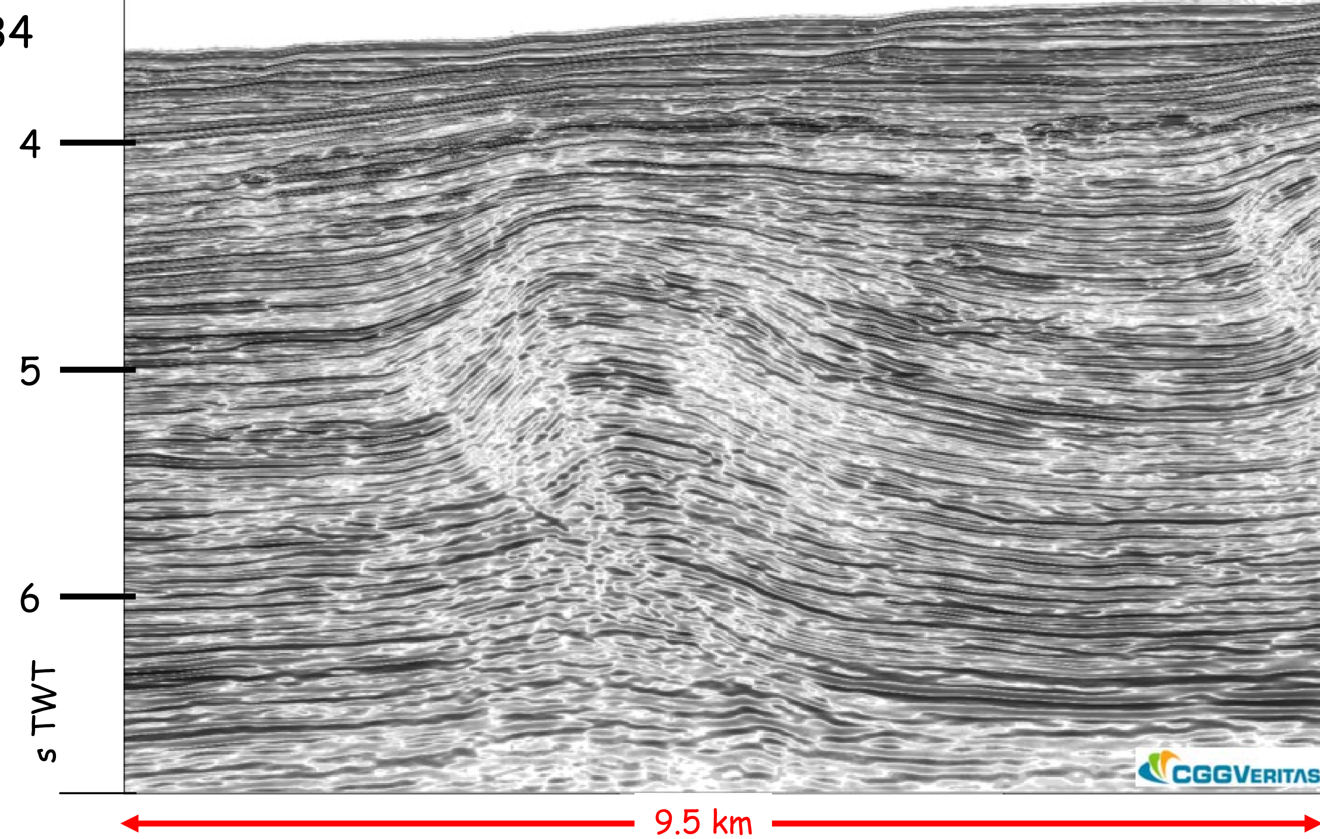




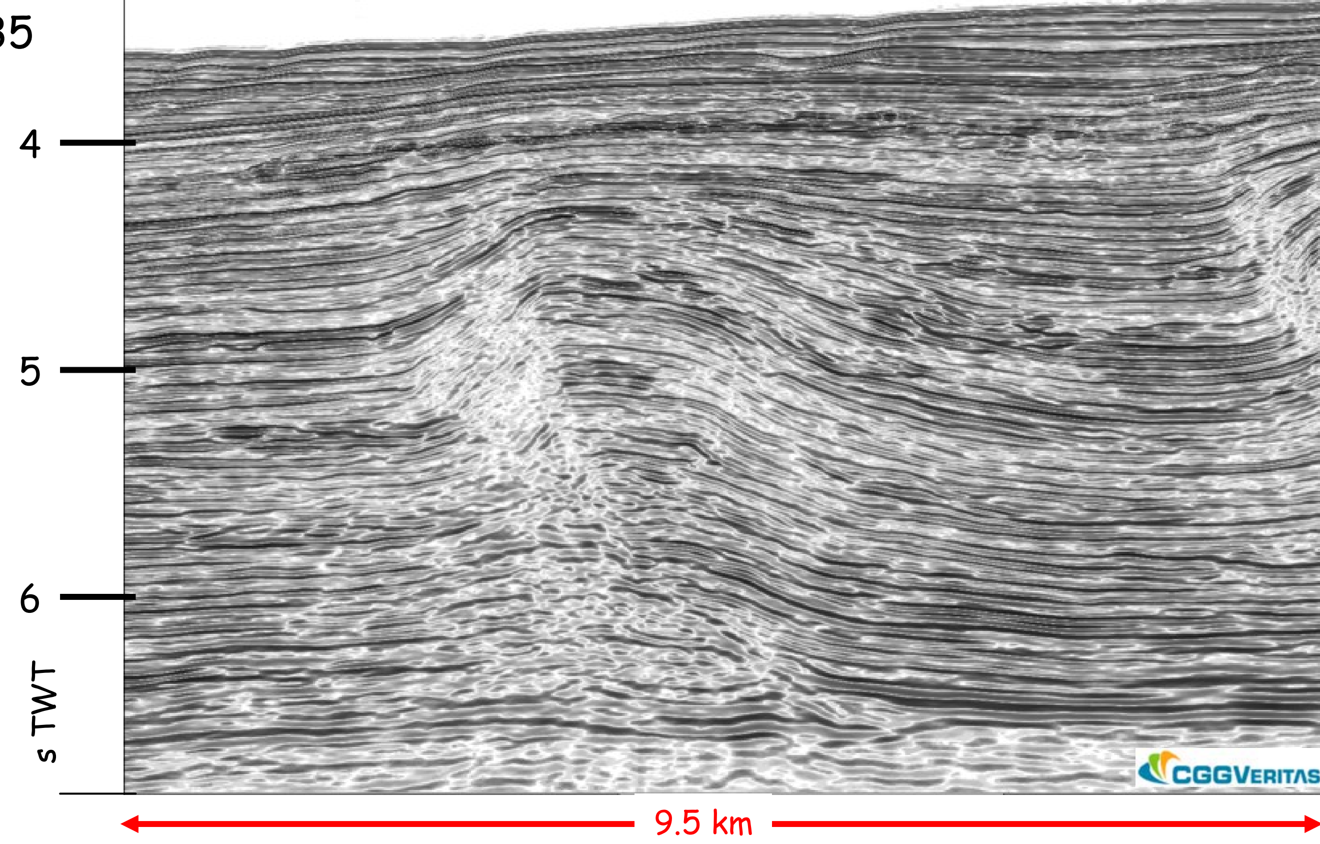
Best fit results:

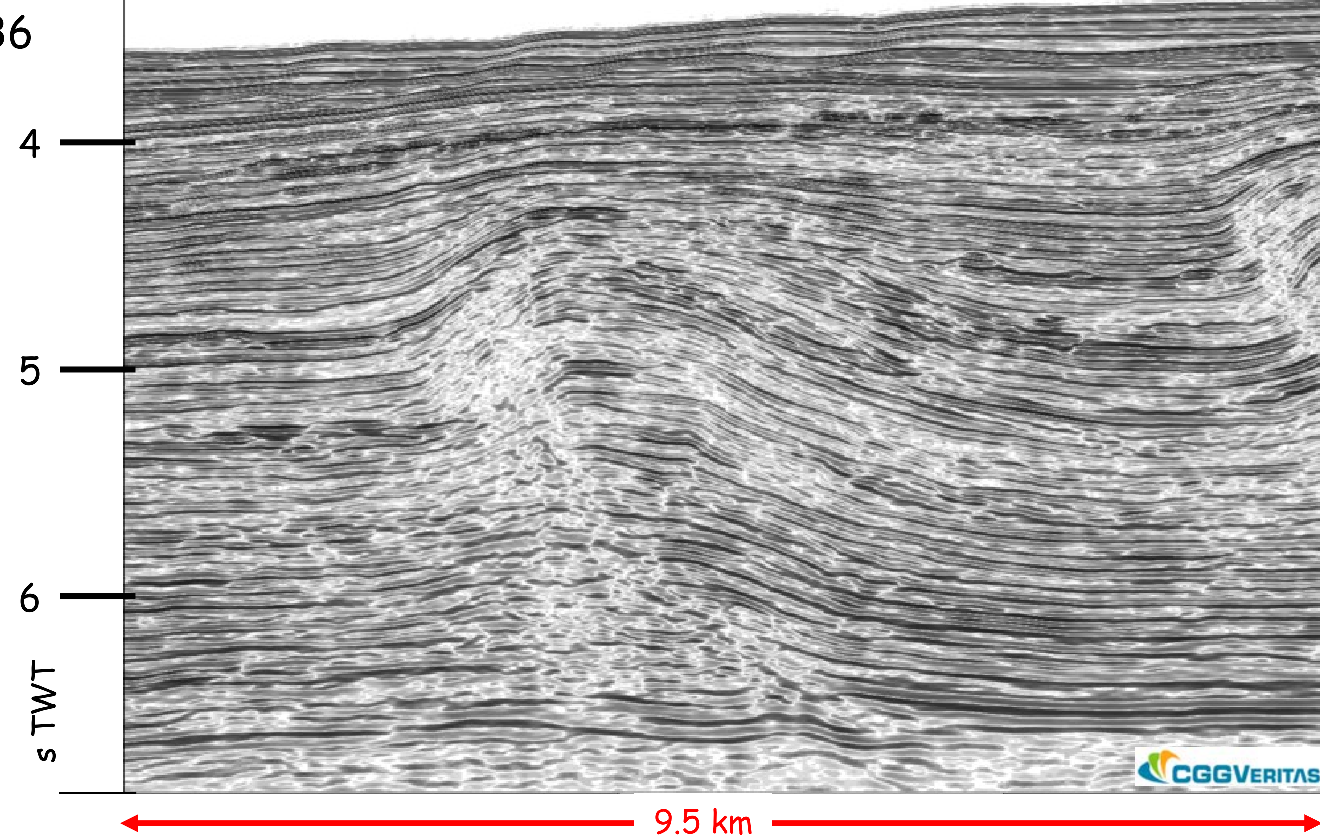
Displacement 200m
Trishear angle 27.1
Propagation/slip 2.3
Trishear angle 110 deg

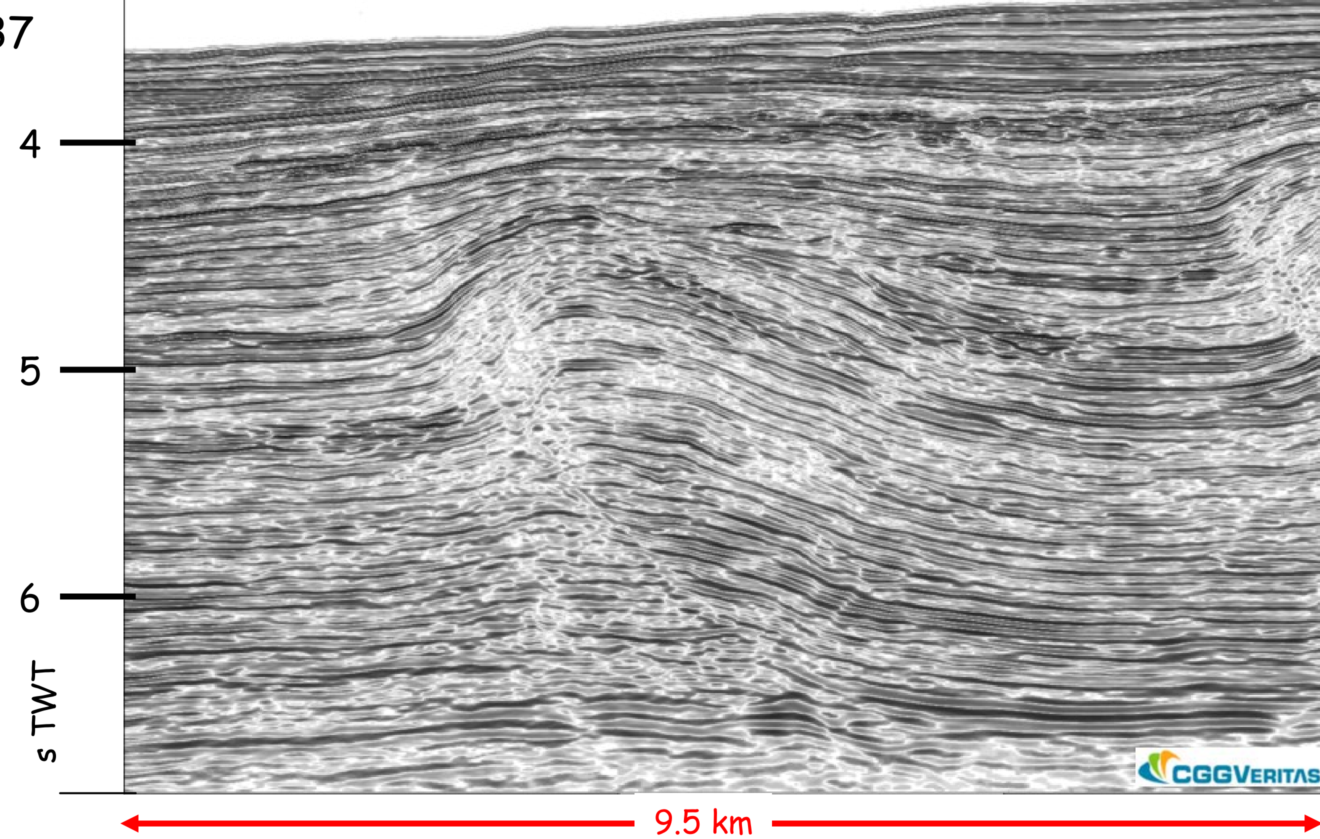




But - does this “best fit” knowledge reduce interpretation uncertainty on adjacent sections?


4
5
6
s TWT
CGGVeritas
9.5 km


4
5
6
s TWT
9.5 km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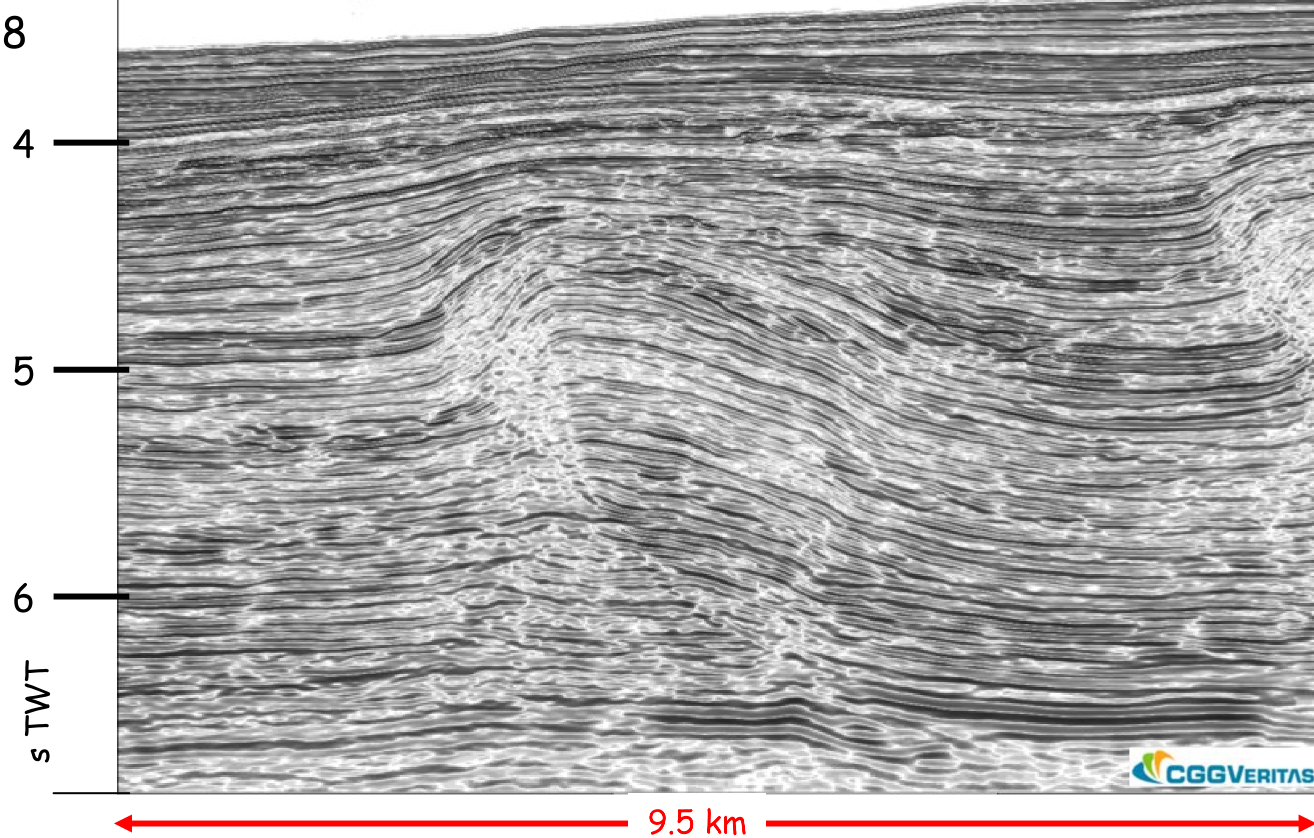
5
6
s TWT
CGGVERITAS
9.5 km


4
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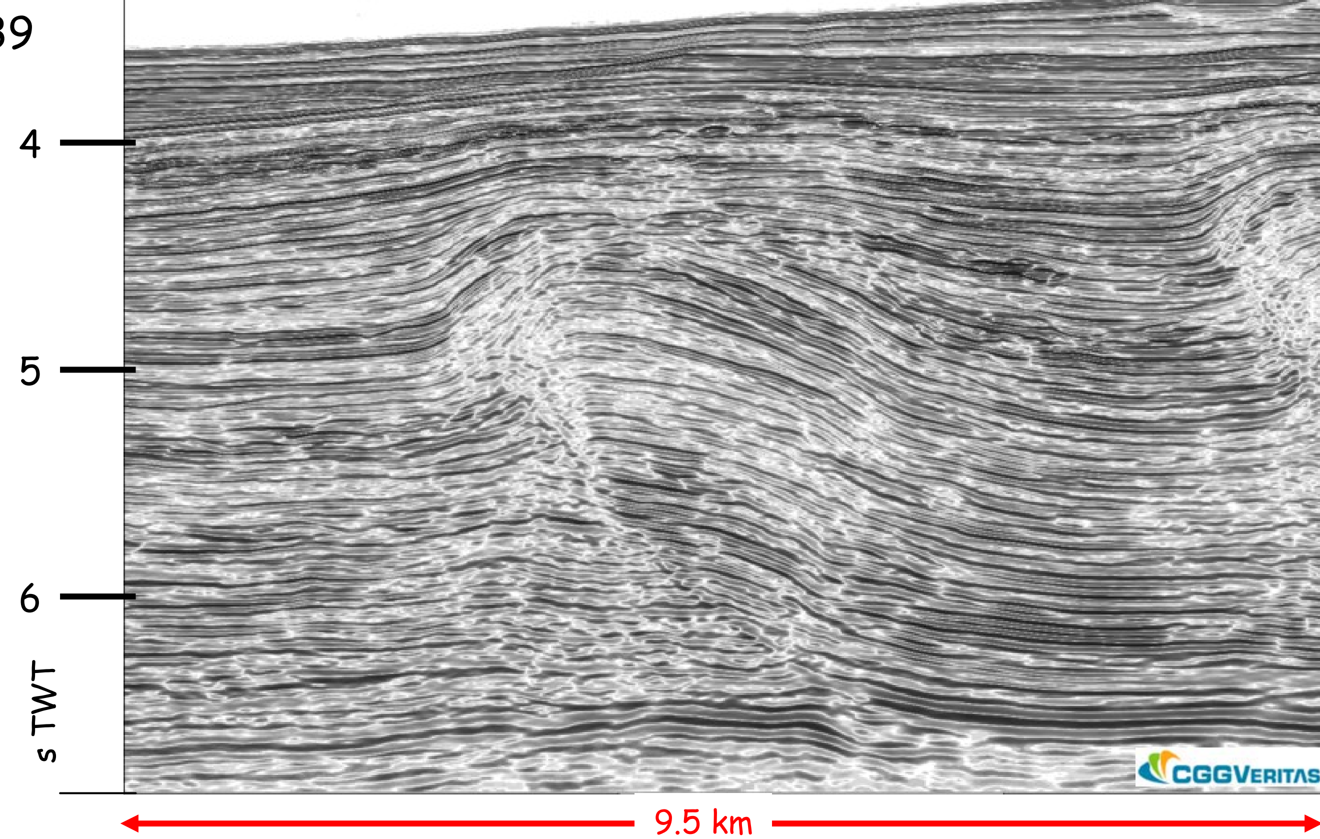
s TWT
9.5 km
CGGVERITAS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5
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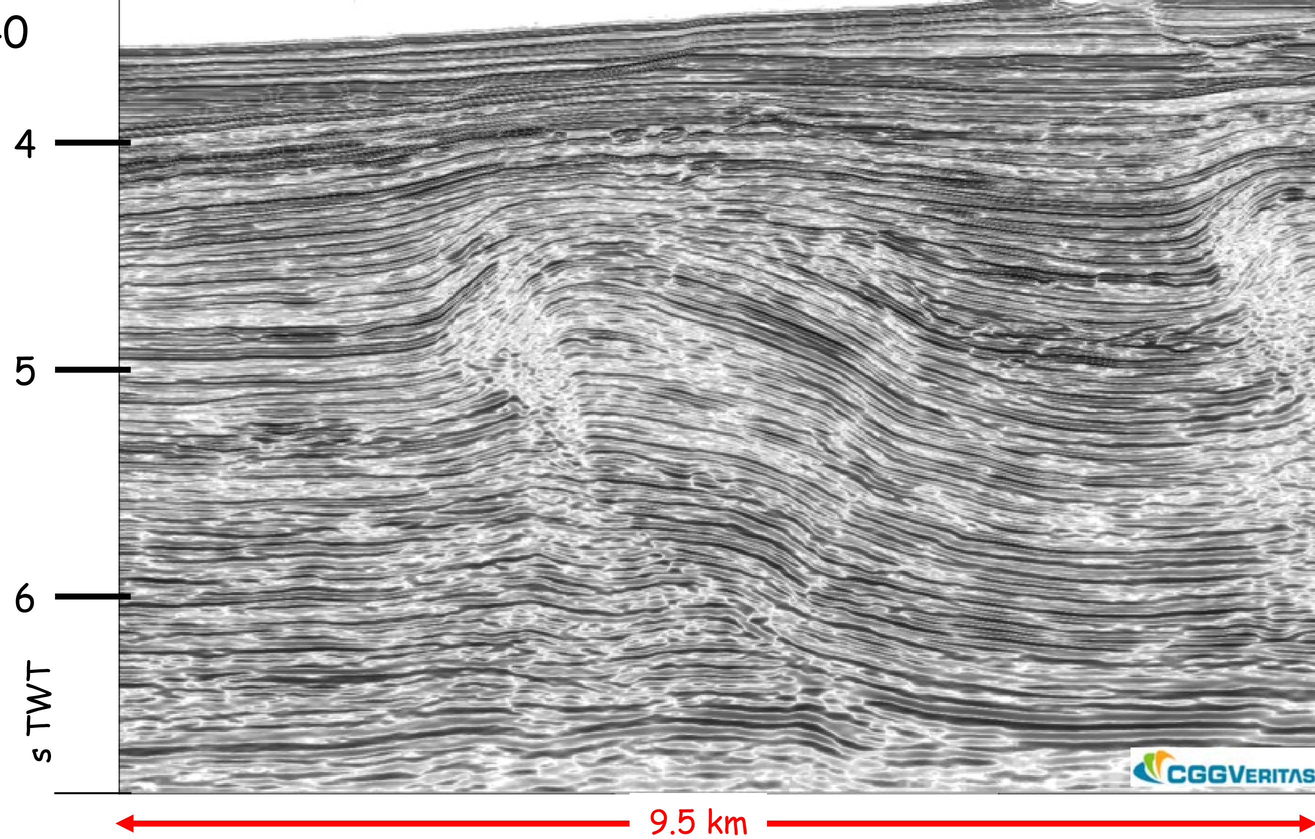
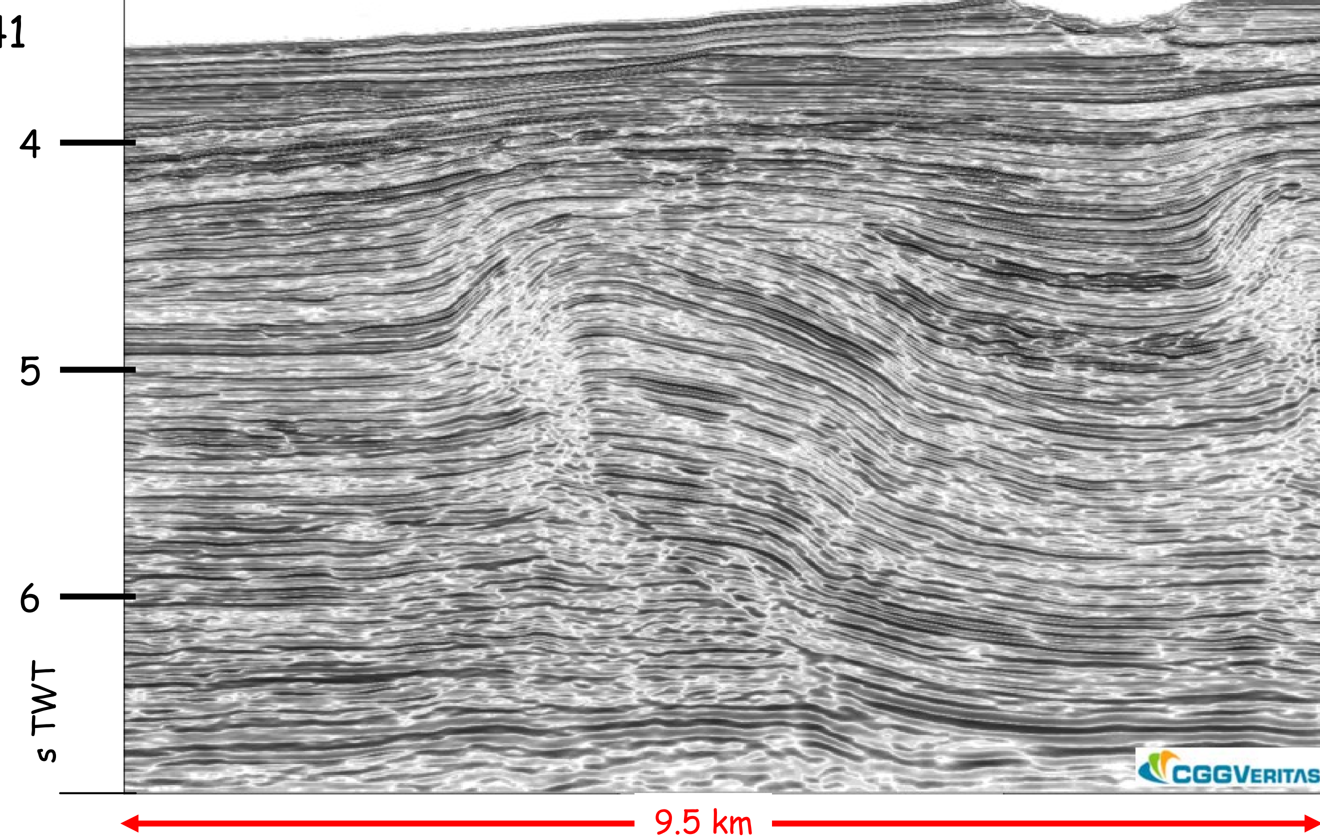
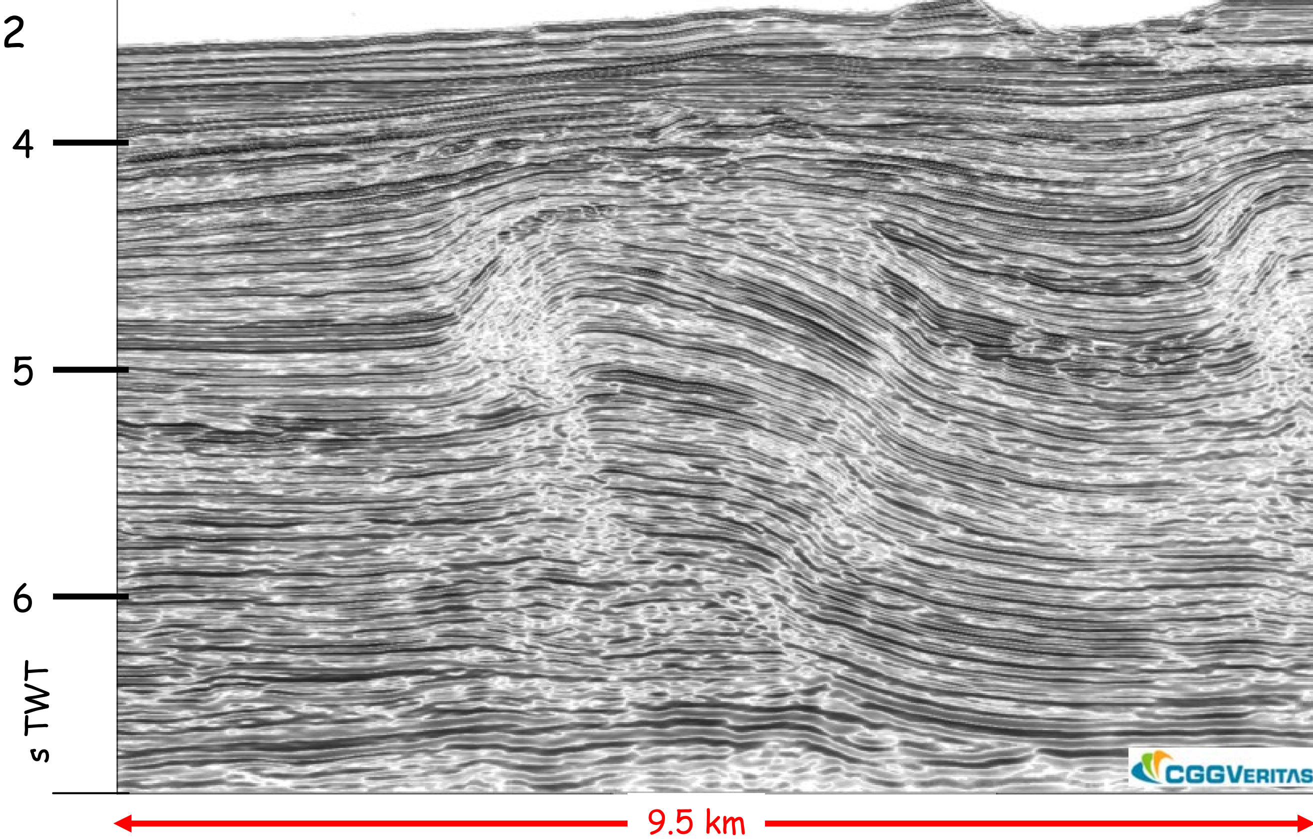
s TWT
CGGVeritas
9.5 km


4
5
6
s TWT
9.5 km

41

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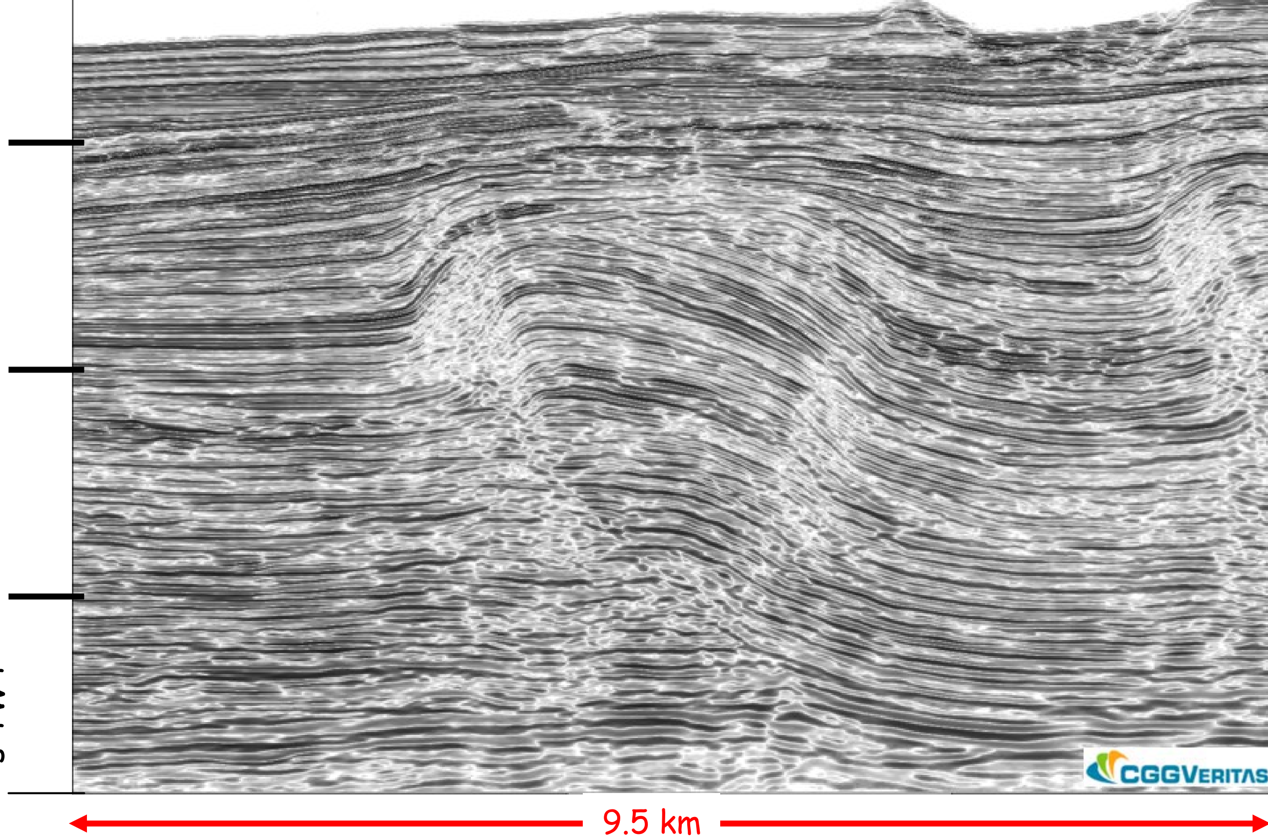
5
6
s TWT
CGGVeritas
9.5 km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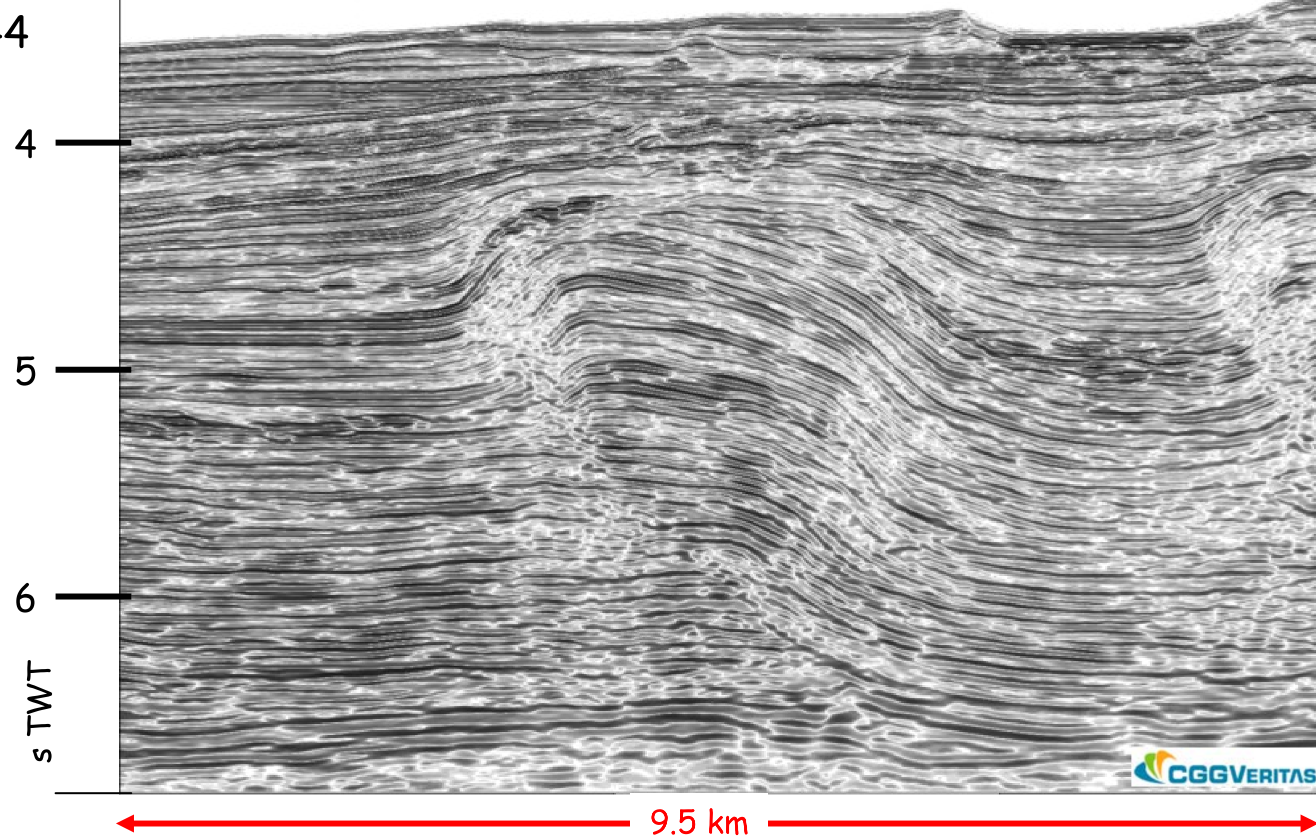
6
s TWT
9.5 km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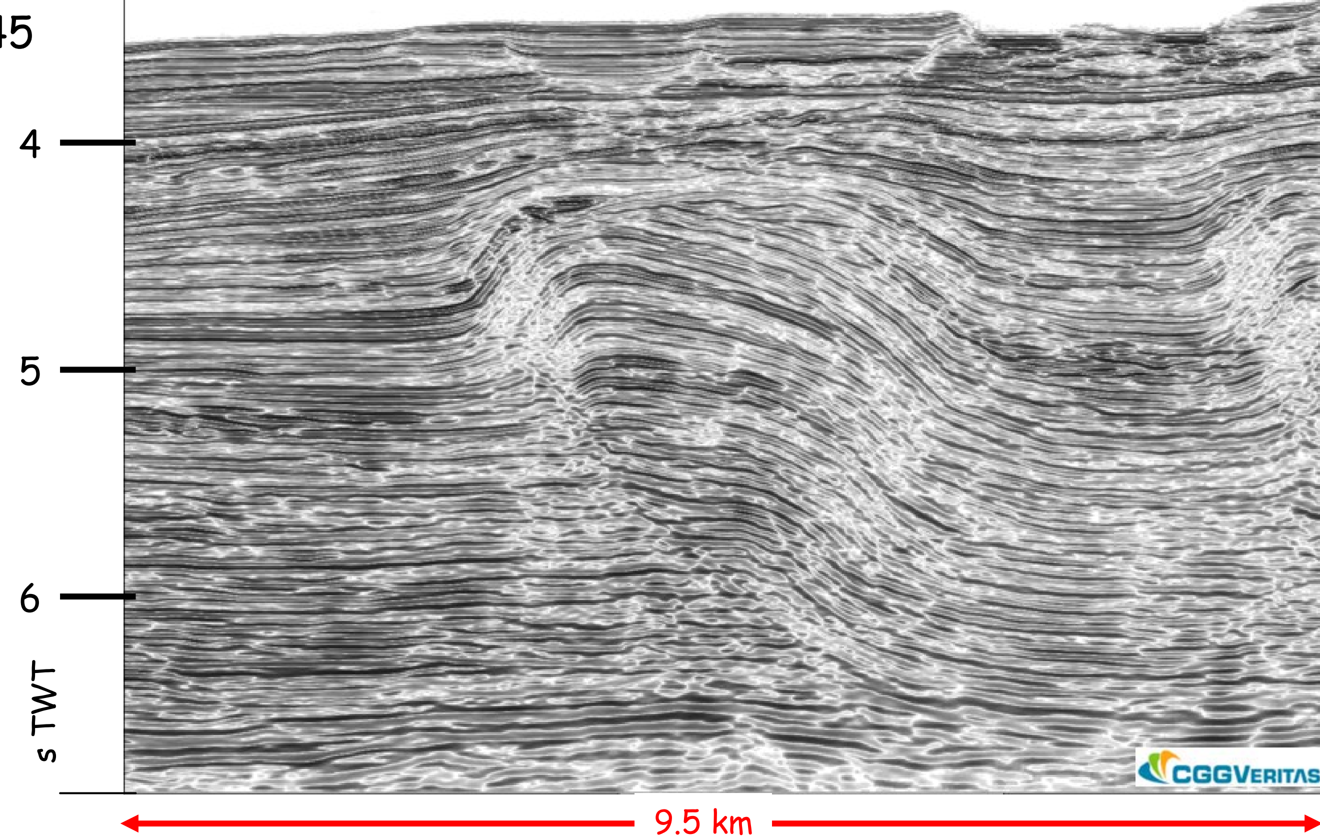
5
6
s TWT
CGGVeritas
9.5 km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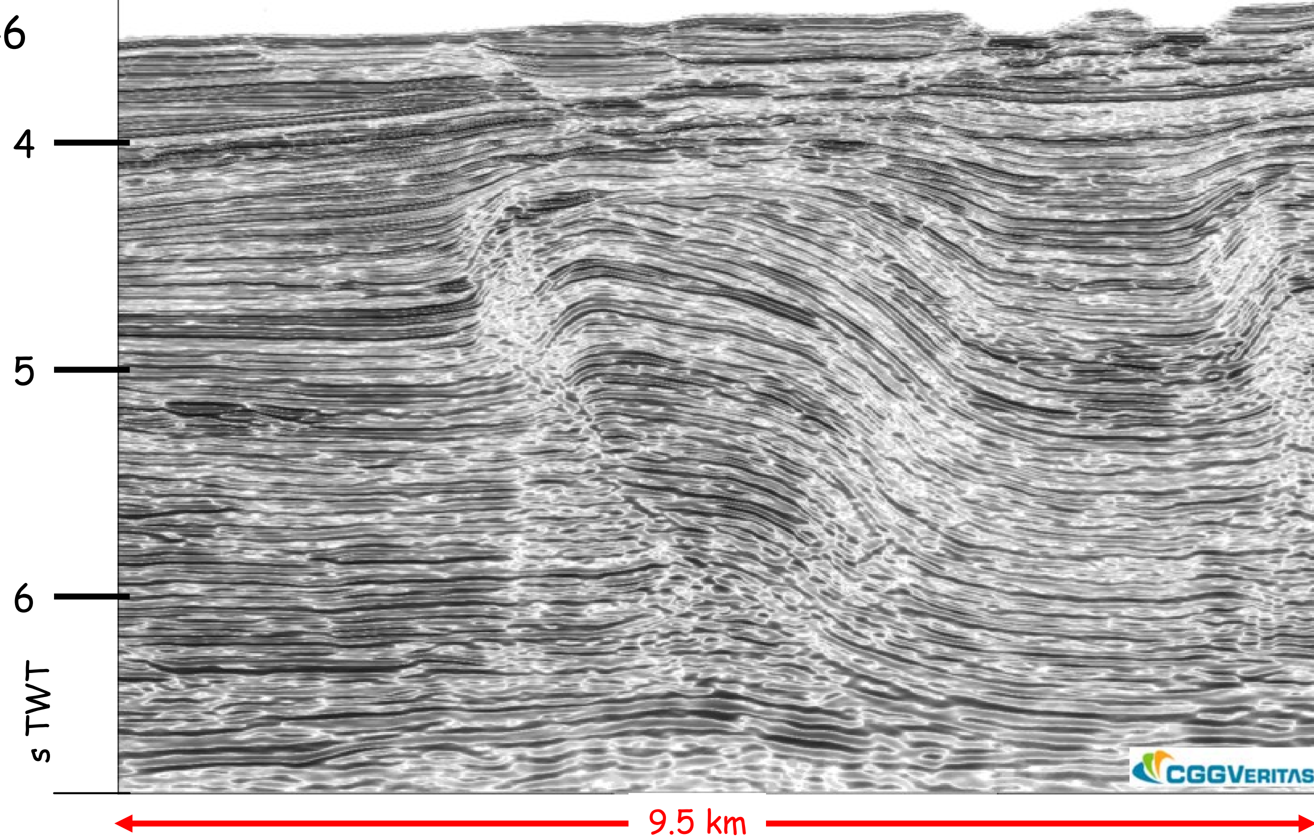
5
6
s TWT
9.5 km
CGGVeritas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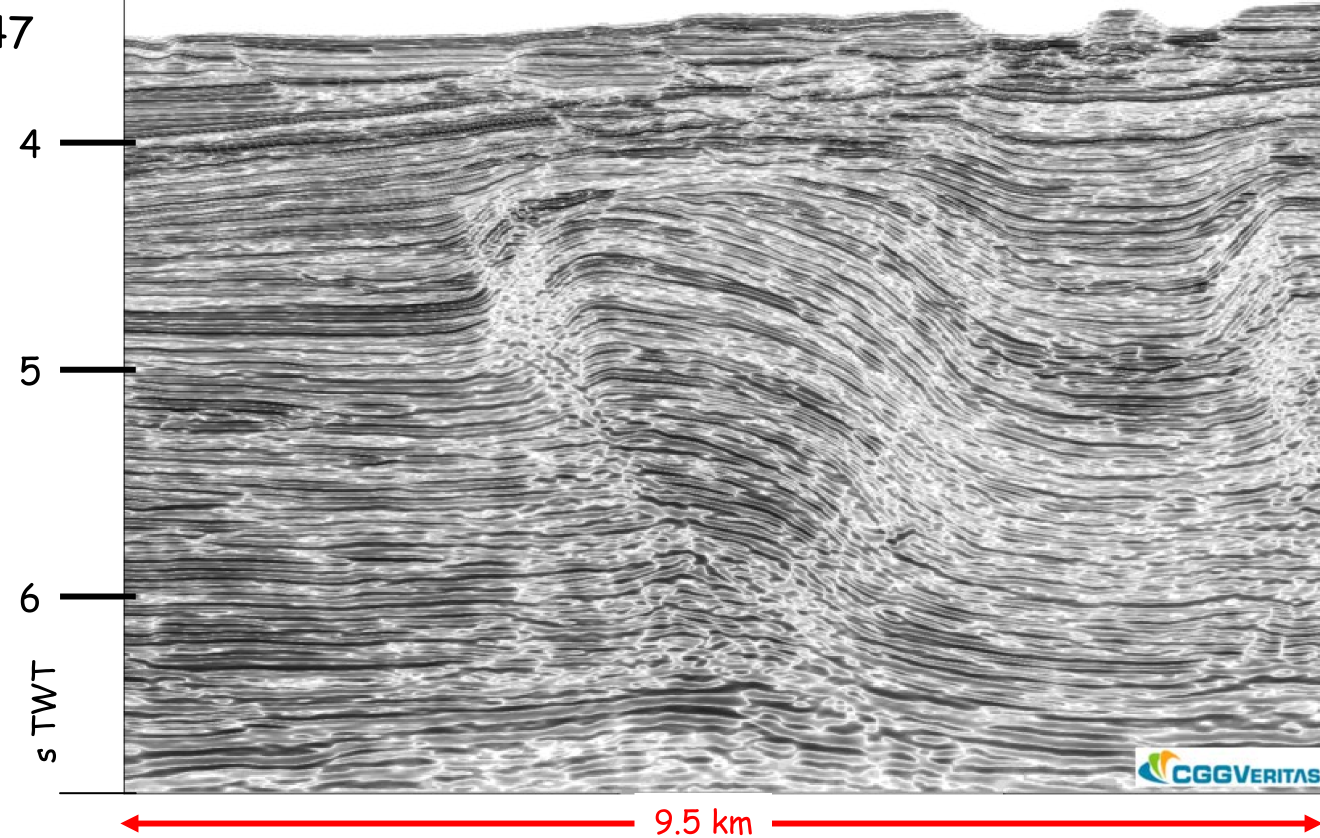
6
s TWT
CGGVeritas
9.5 km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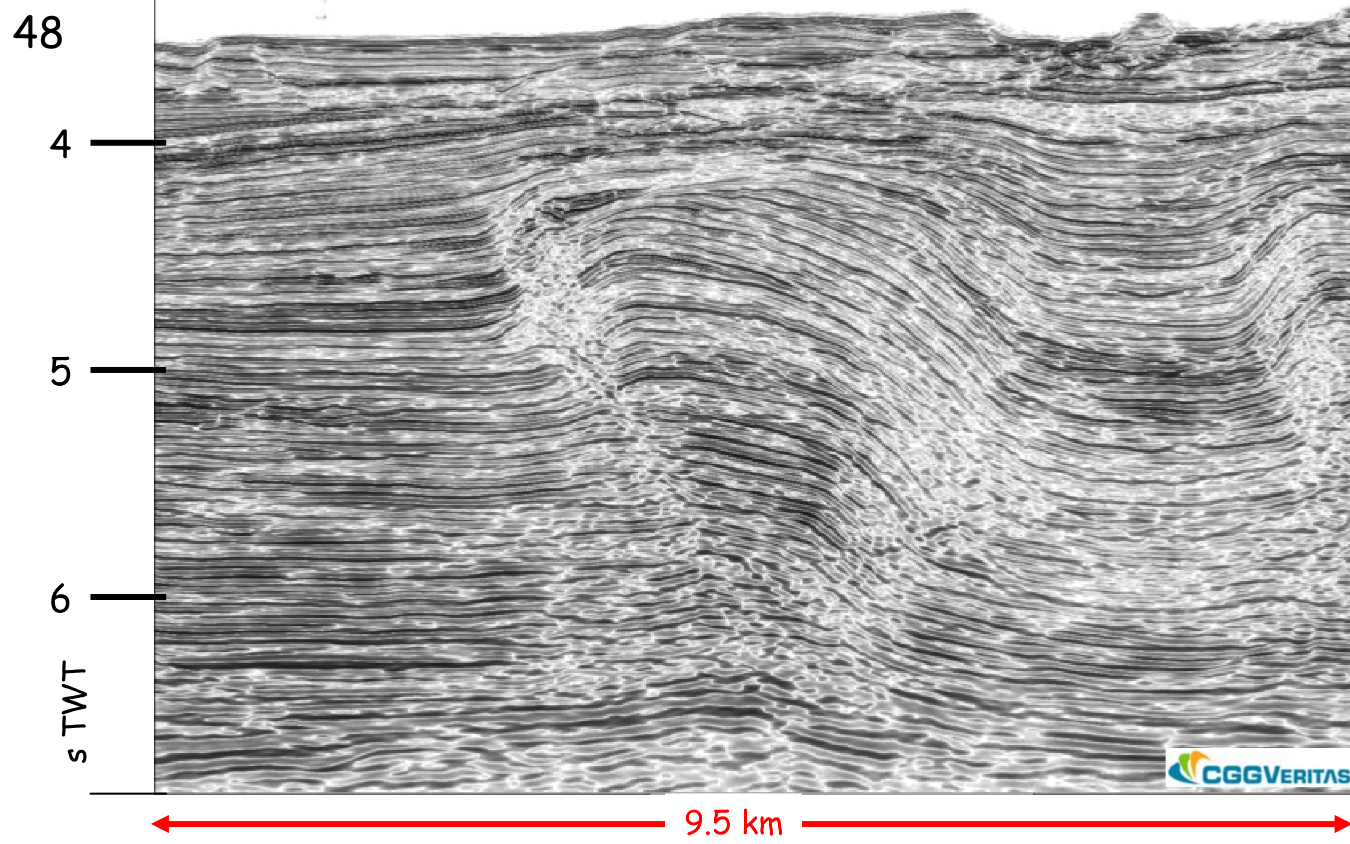
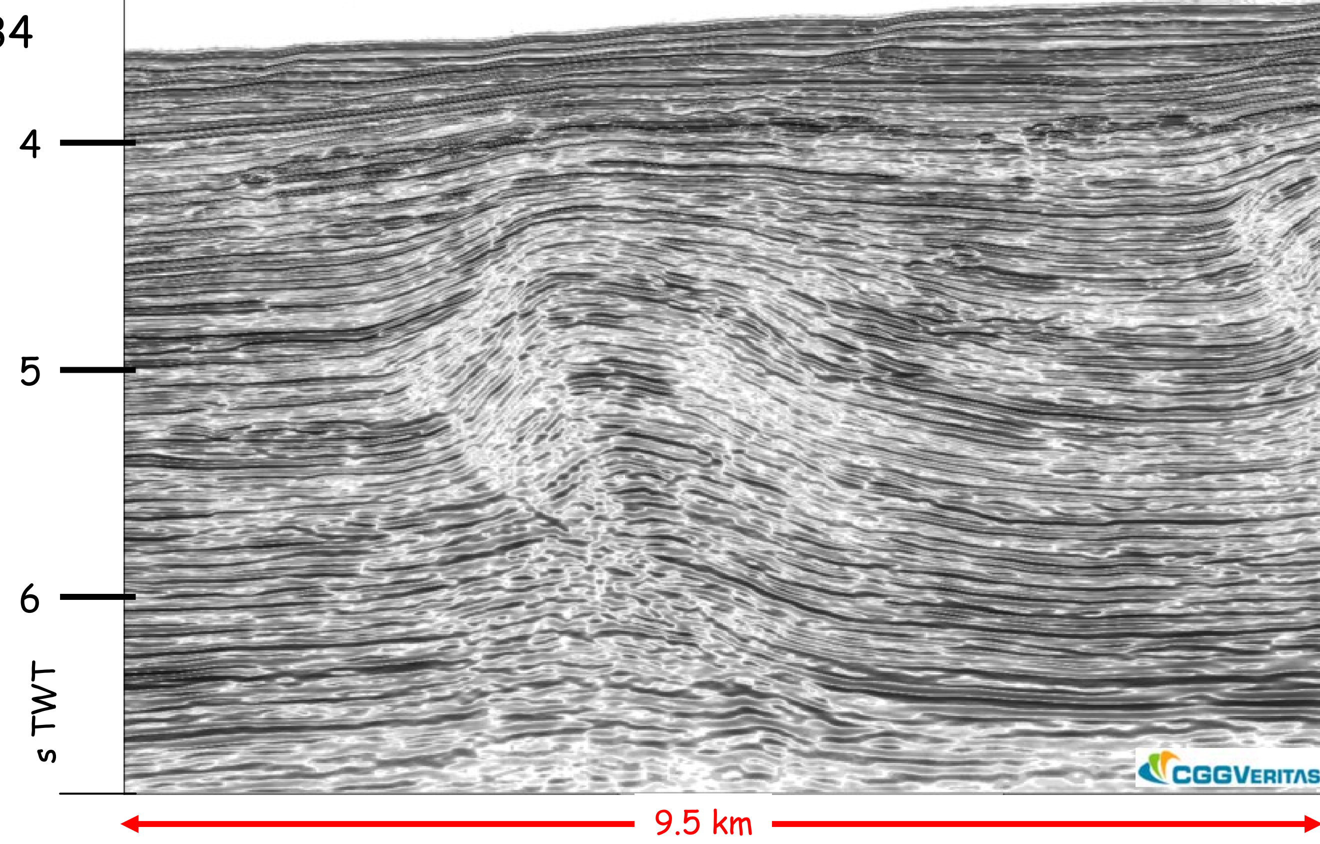
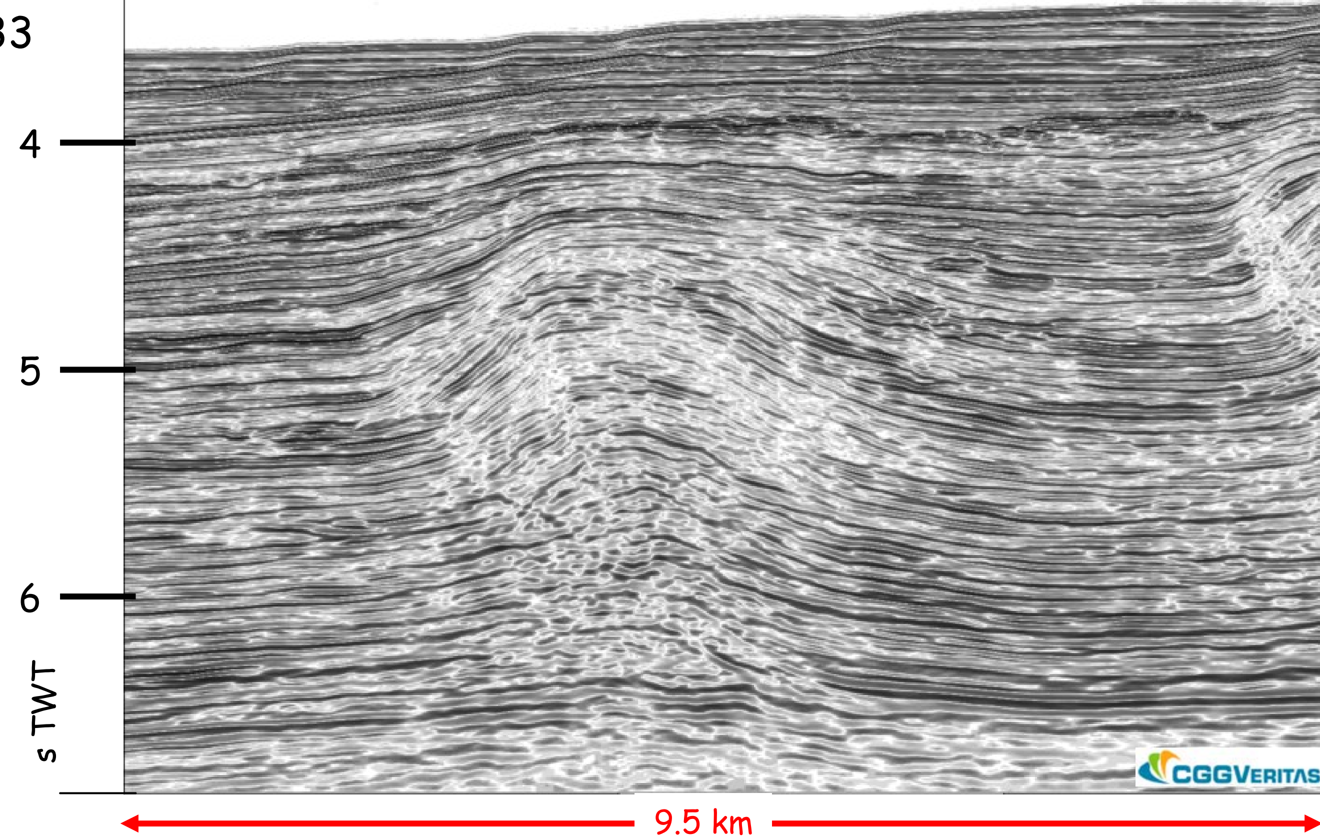
s TWT
9.5 km
CGGVeritas



All that happened in 3.5 km…



What about in the other direction…?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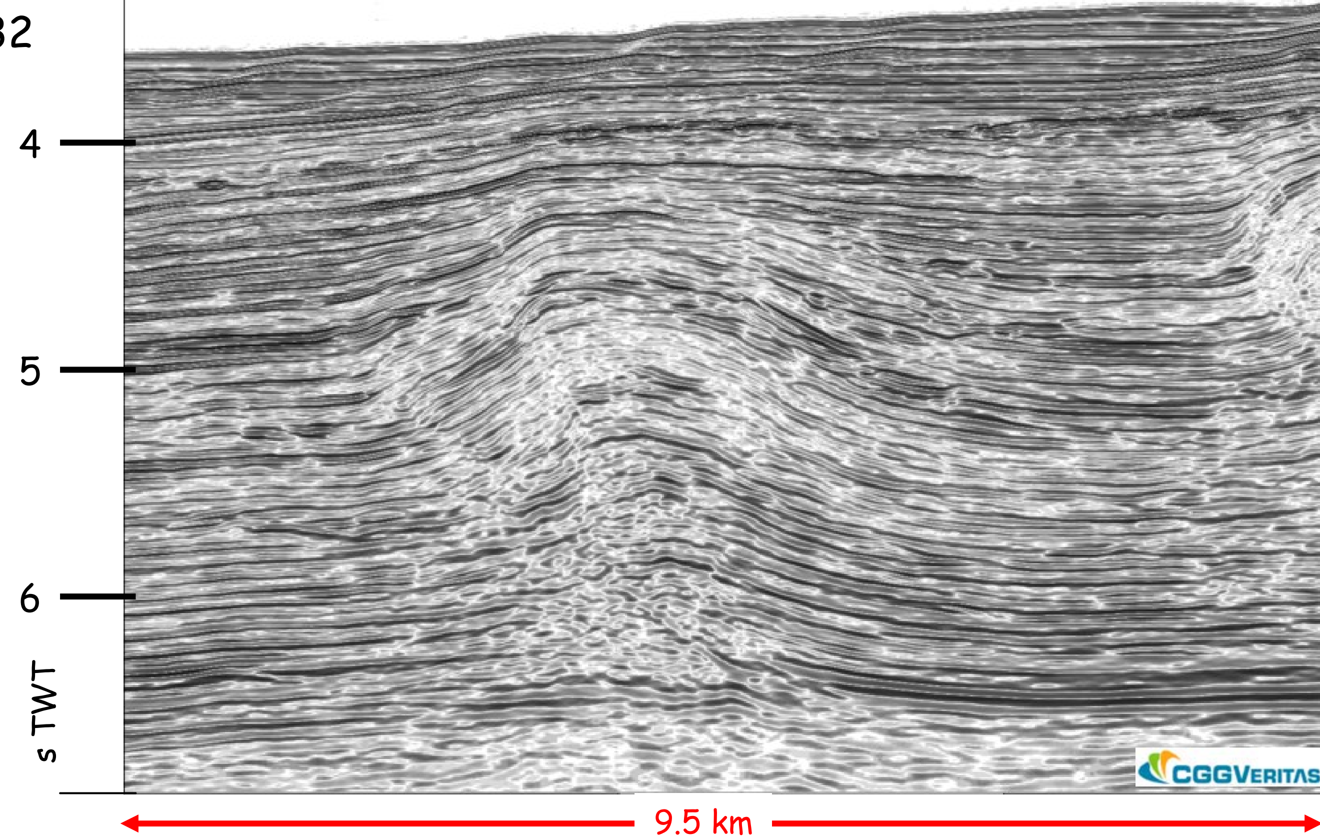
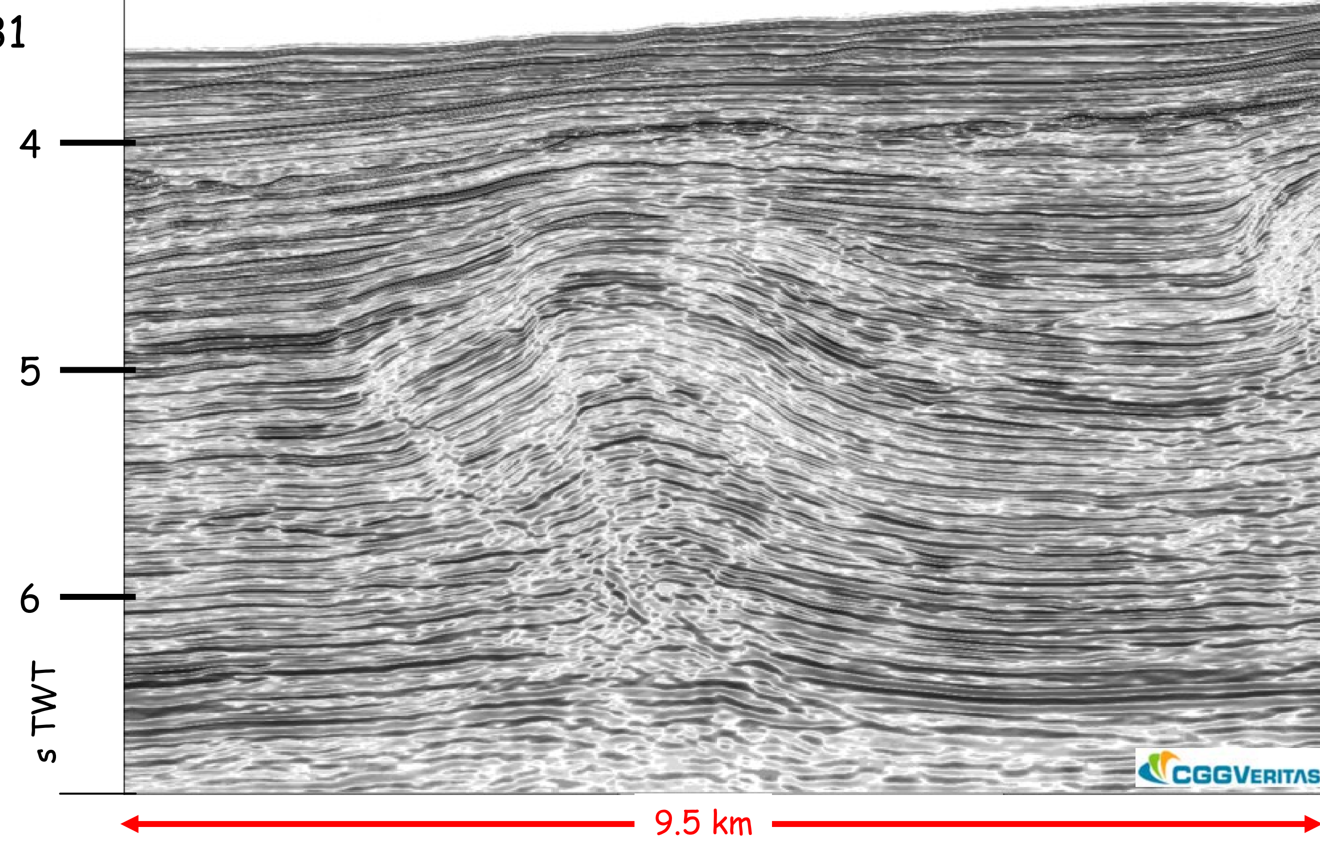
5
6
s TWT
CGGVeritas
9.5 km


4
5
6
s TWT
9.5 km
CGGVeritas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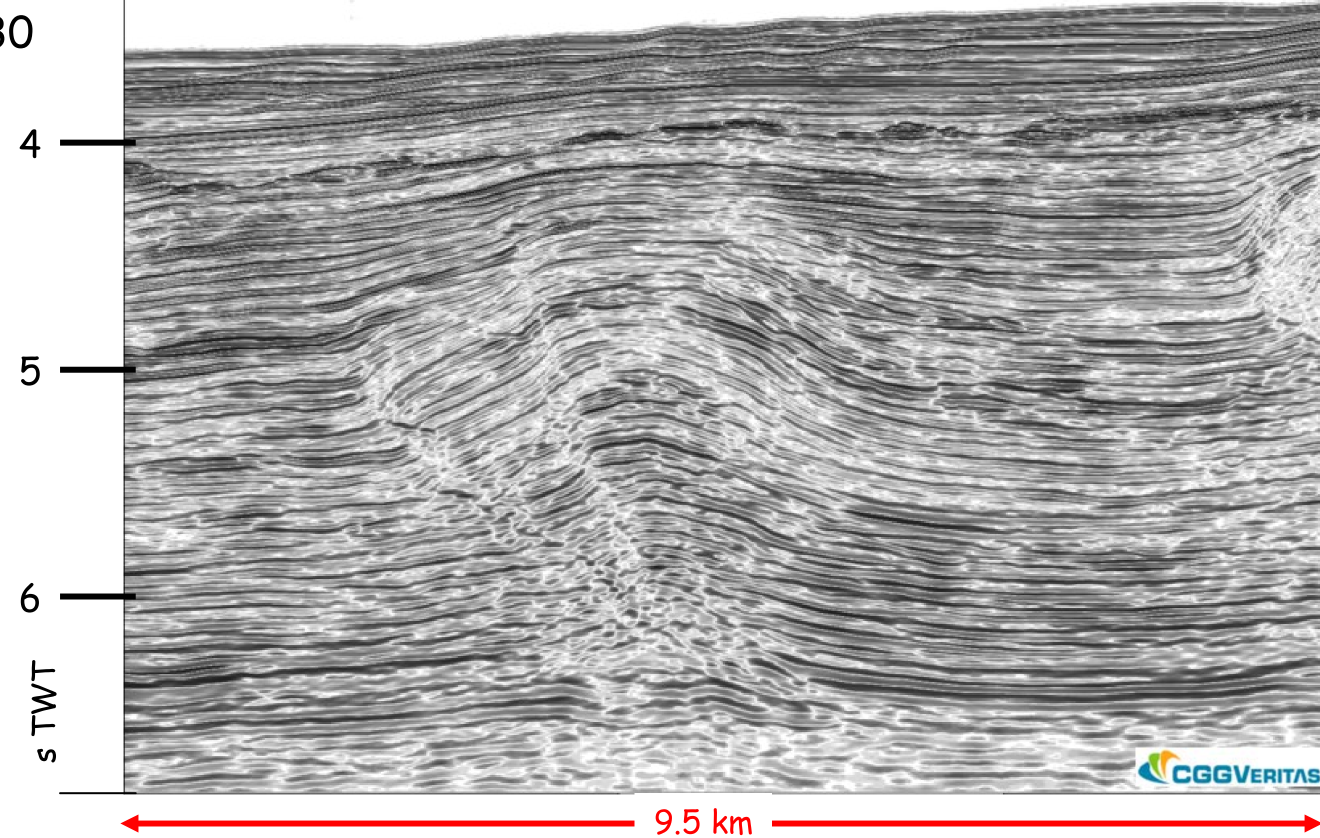
5
6
s TWT
CGGVERITAS
9.5 km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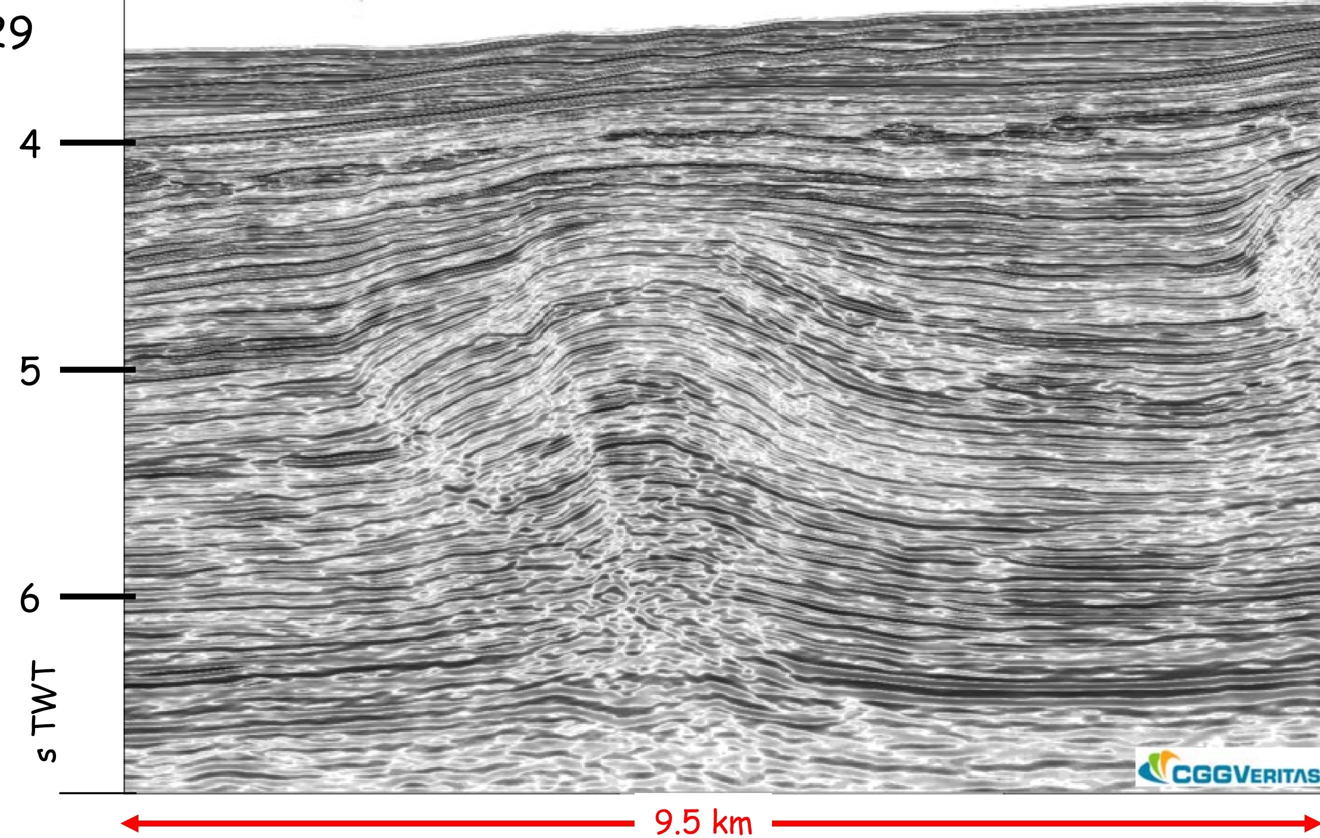
s TWT
CGGVeritas
9.5 km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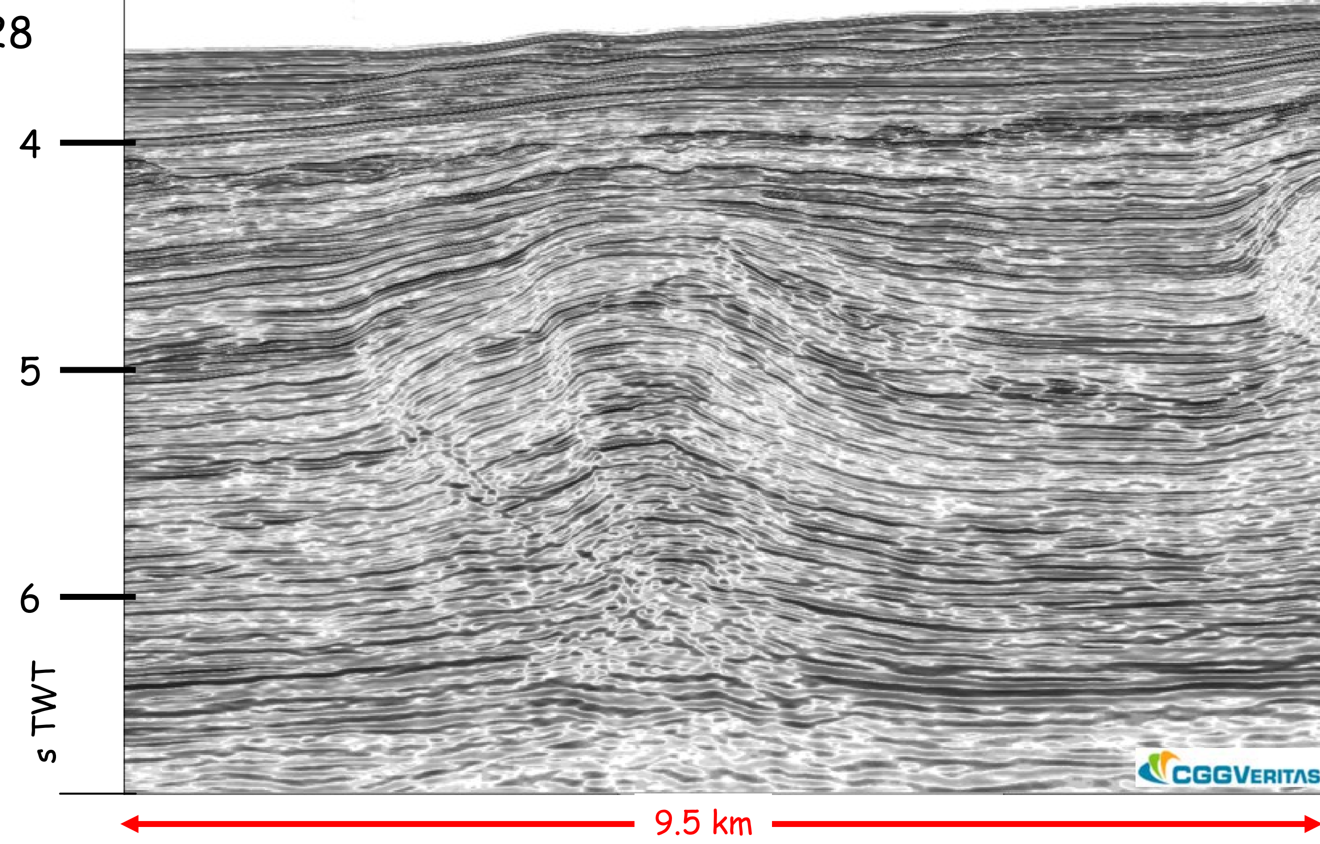
5
6
s TWT
9.5 km
CGGVeritas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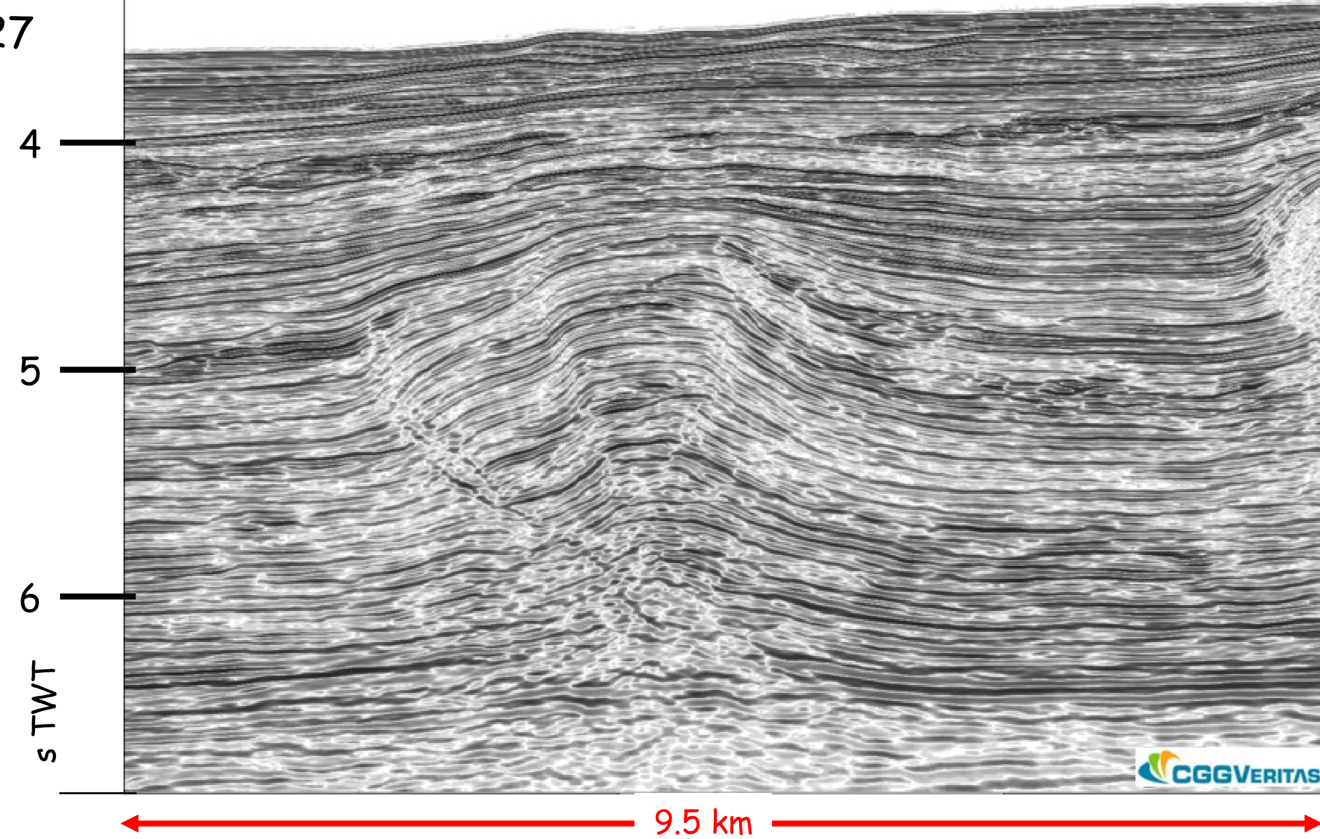
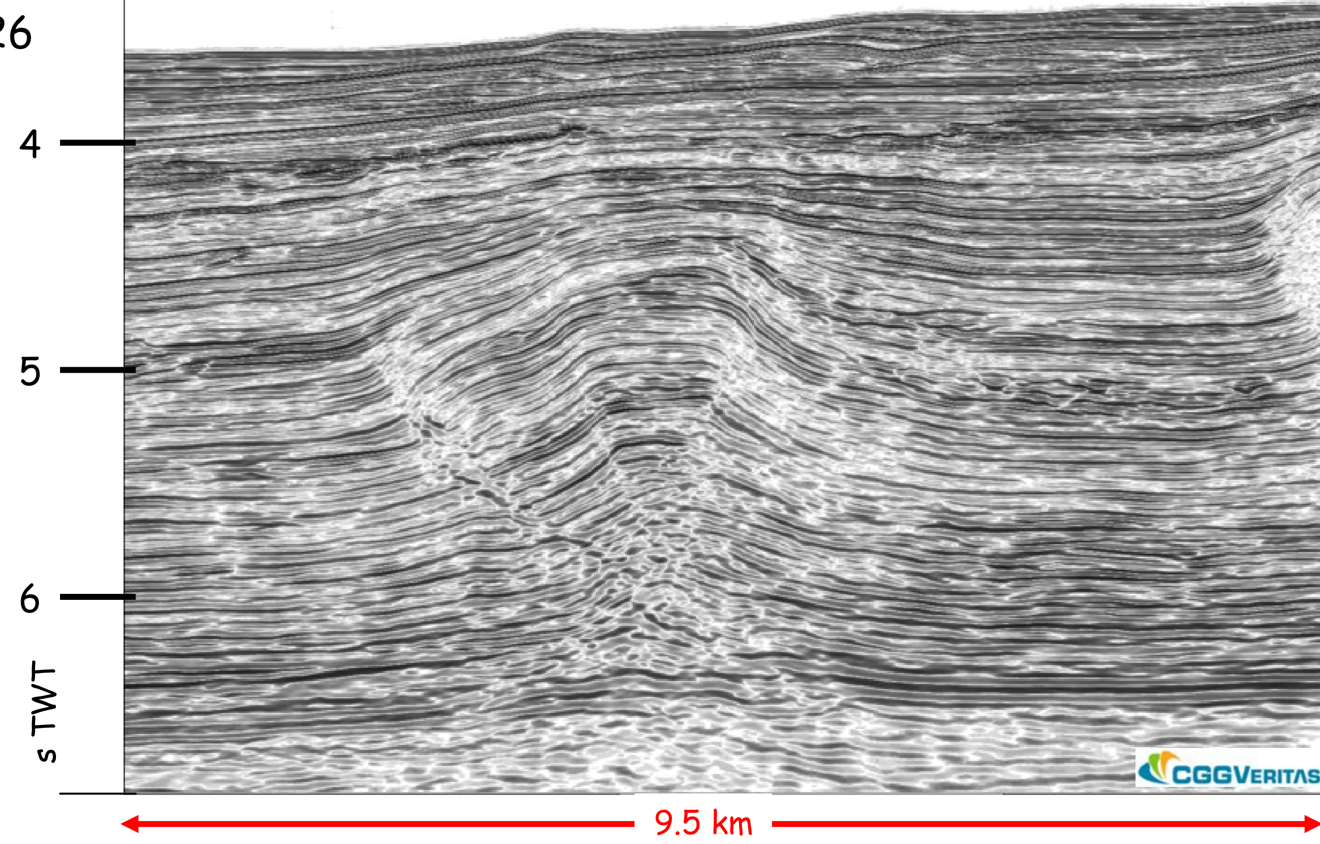
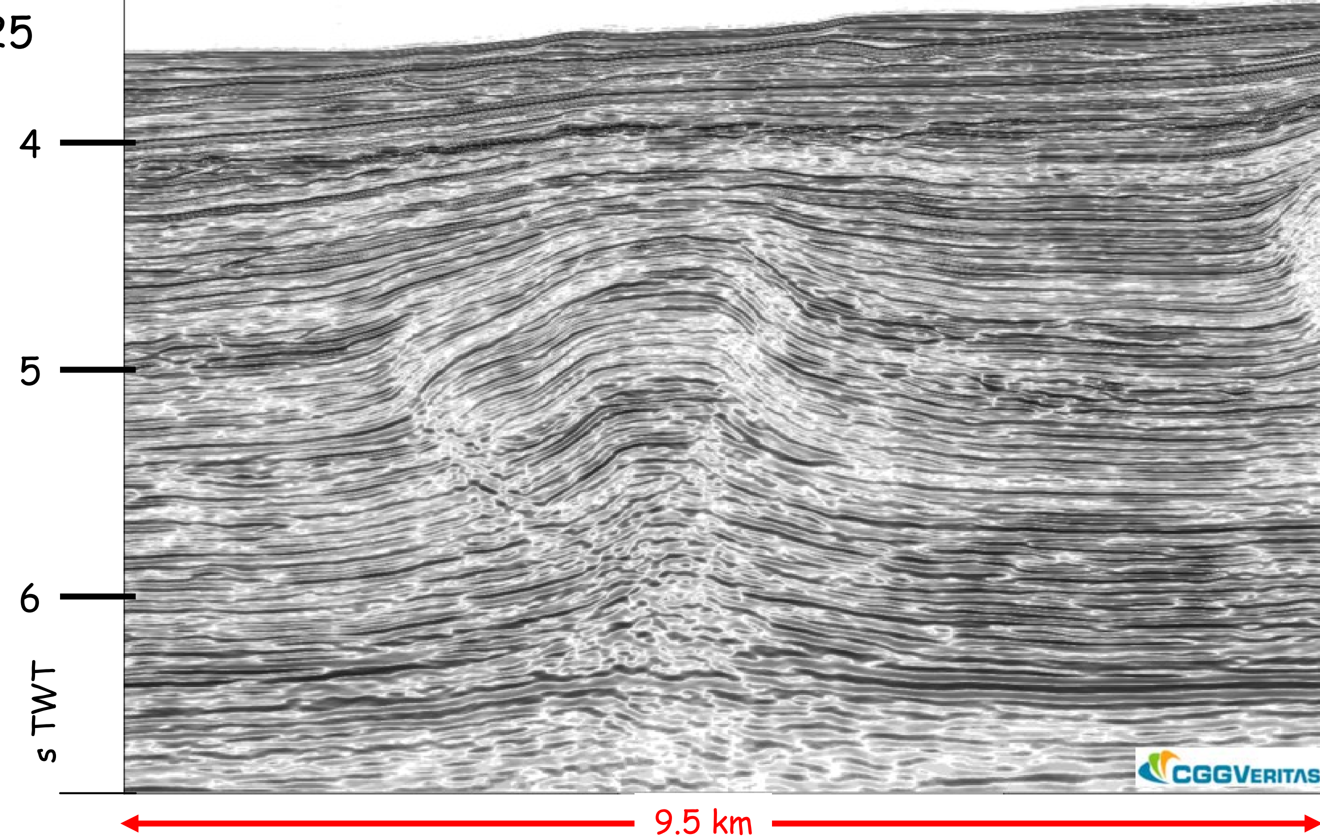
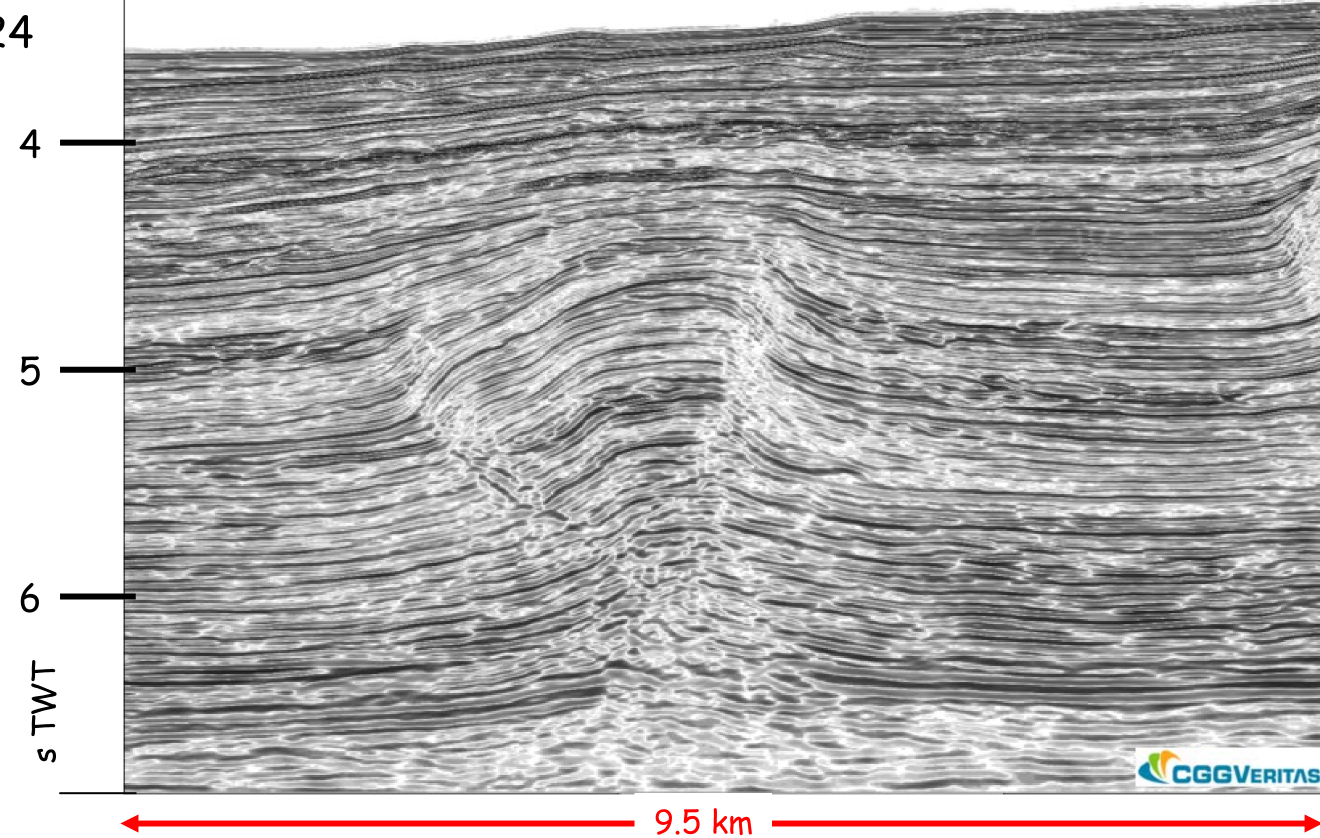
5
6
s TWT
CGGVeritas
9.5 km

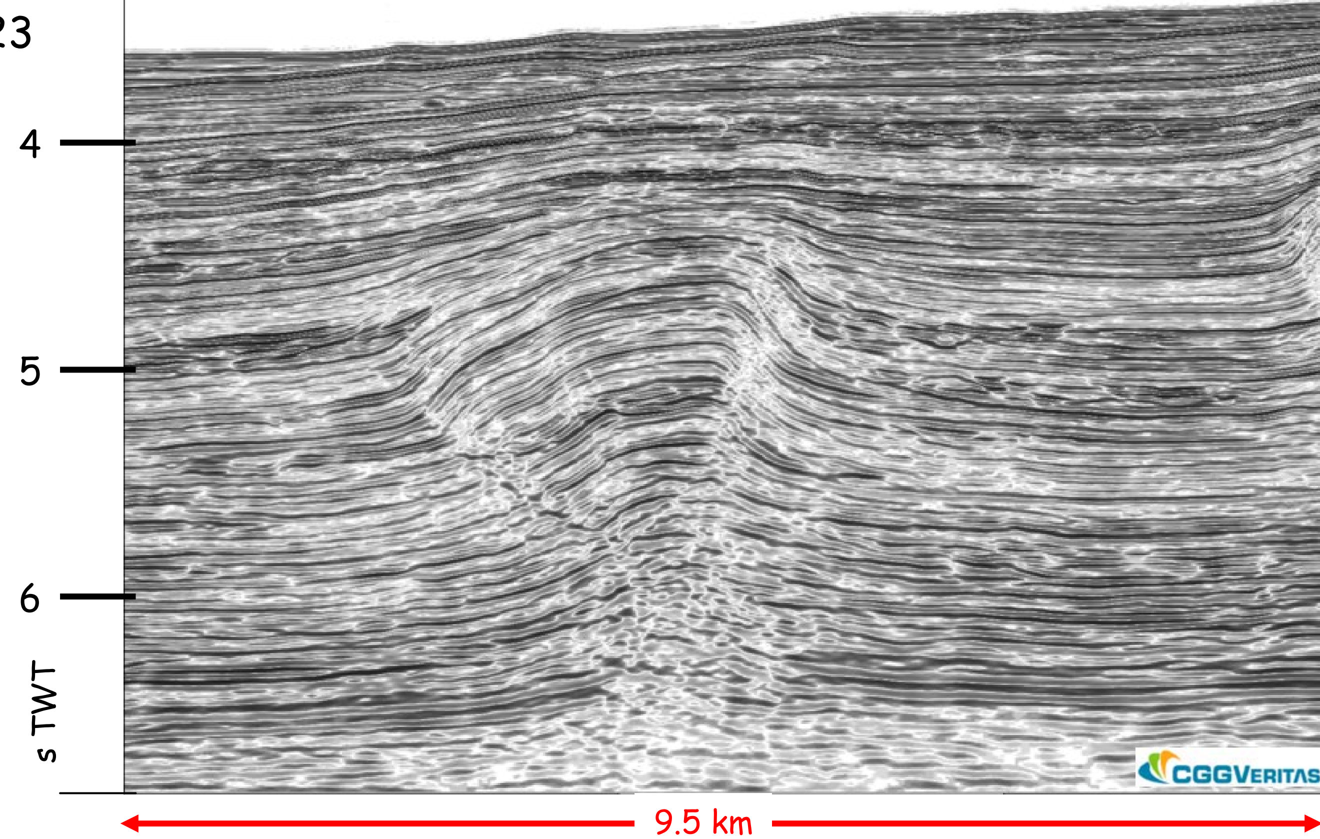

4
5
6
s TWT
9.5 km
CGGVeritas

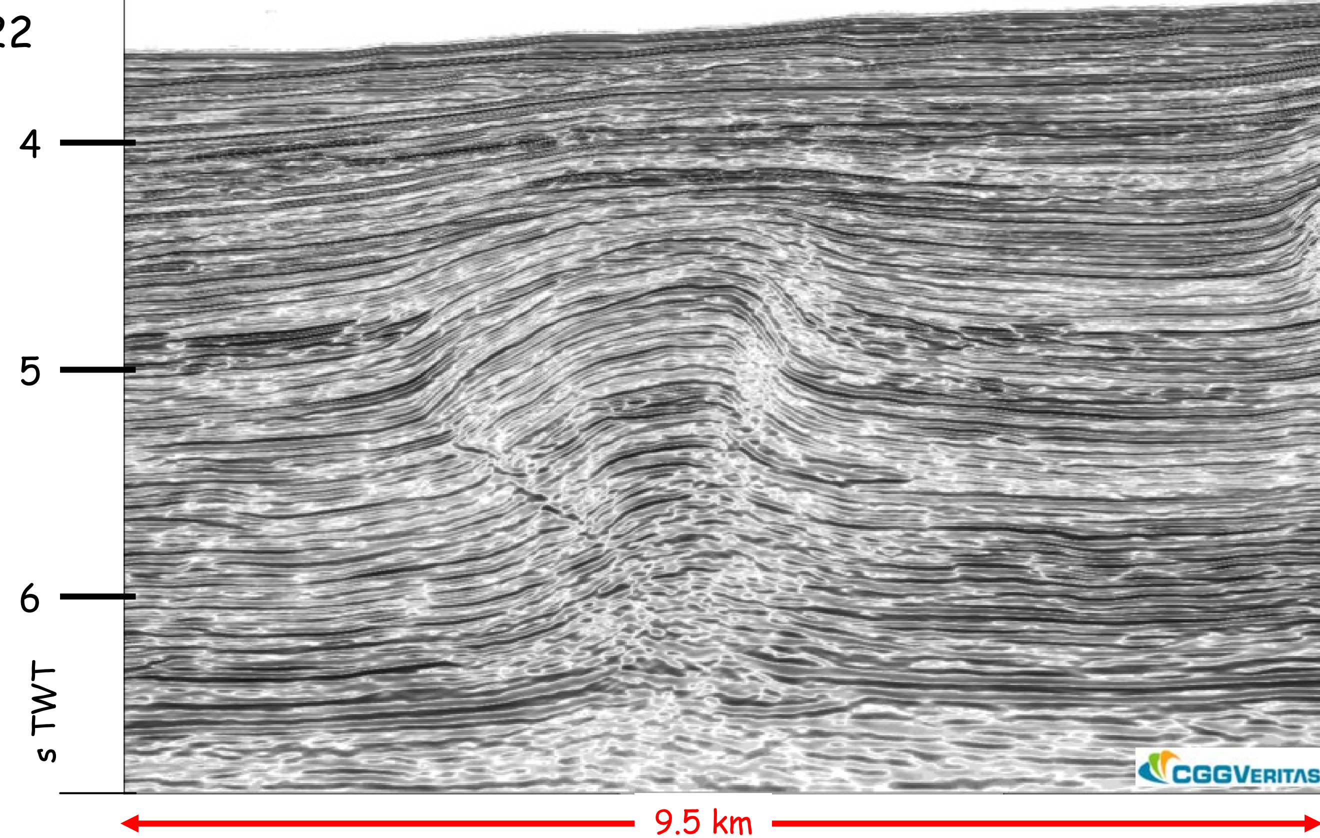

4
5
6
s TWT
9.5 km


4
5
6
s TWT
CGGVERITAS
9.5 km

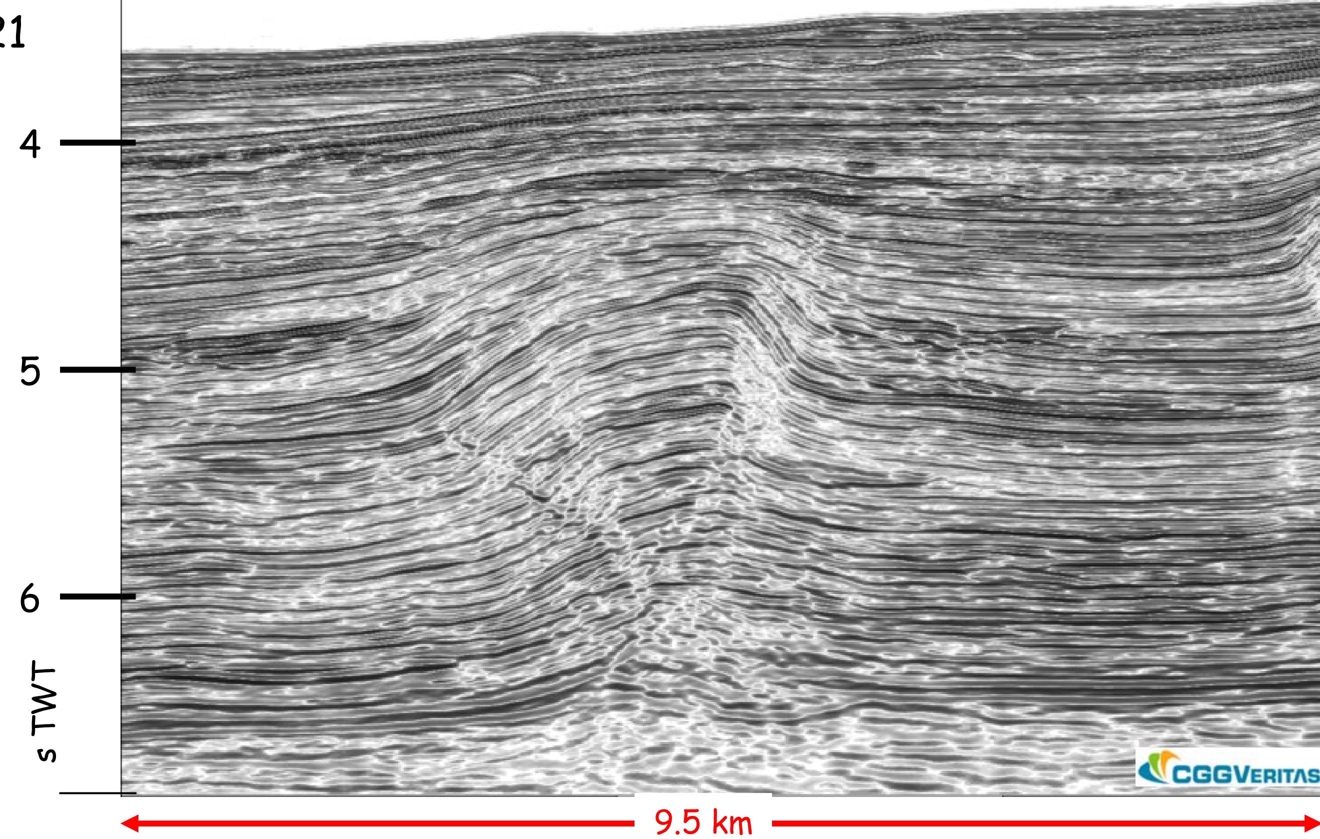

4
5
6
s TWT
9.5 km

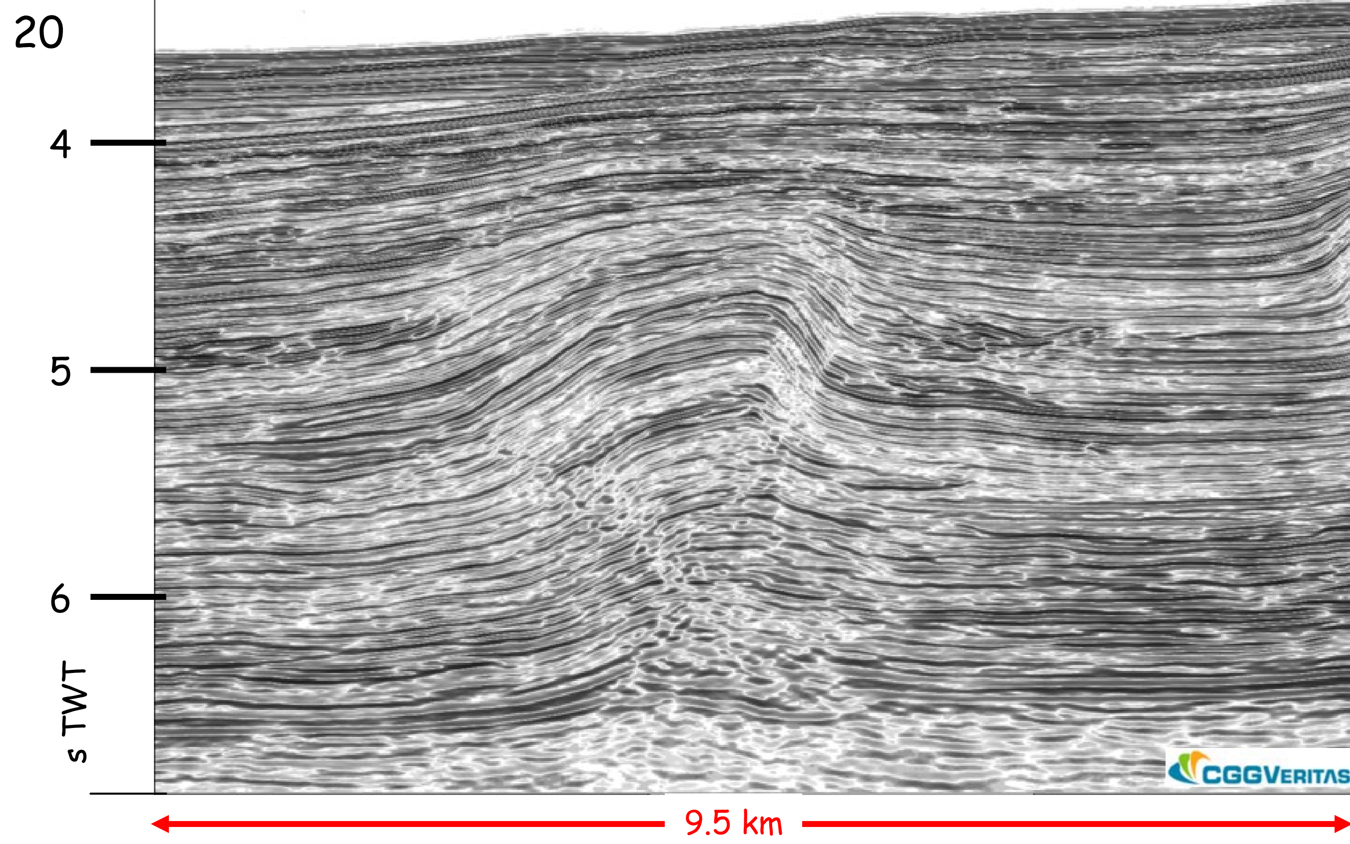
23

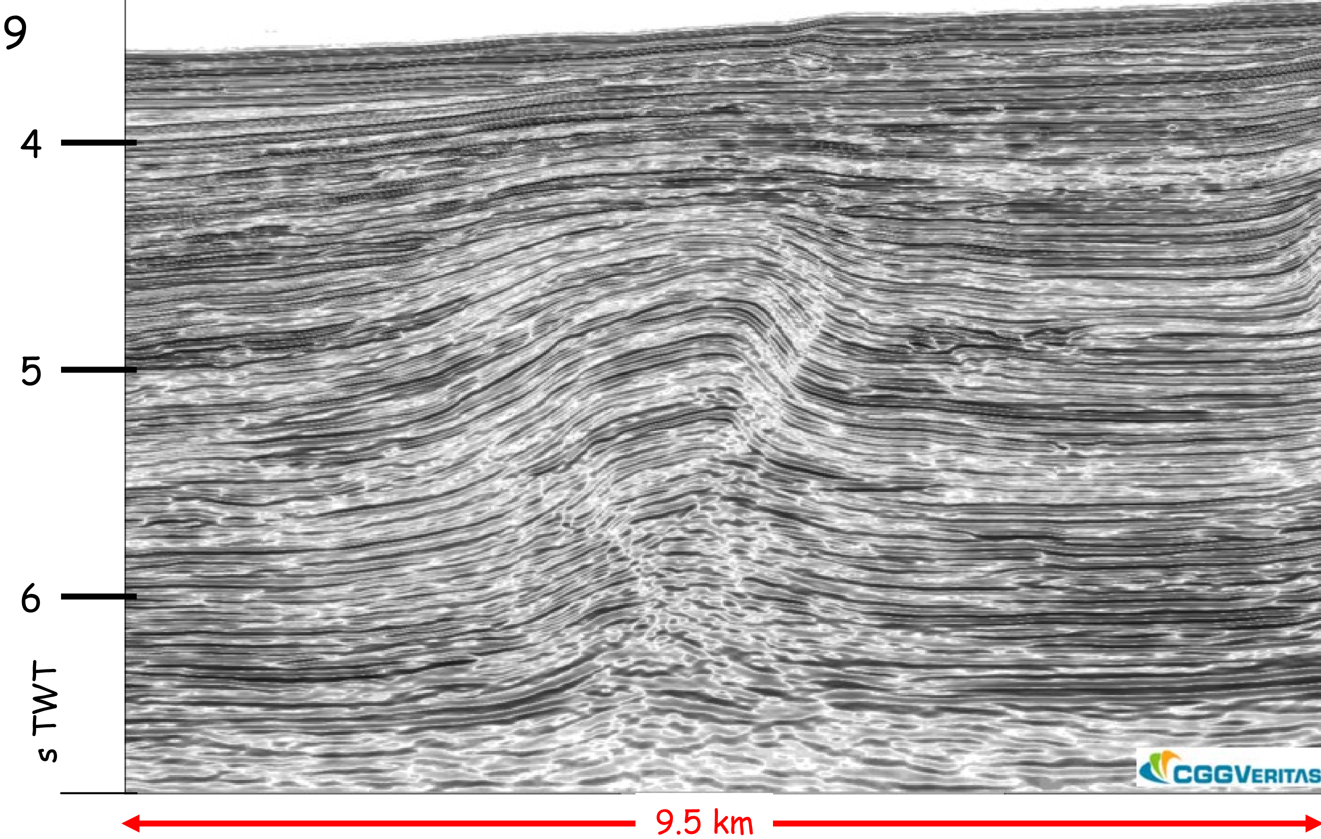



4
5
6
s TWT
9.5 km

21




20
4
5
6
s TWT
CGGVeritas
9.5 km


4
5
6
s TWT
CGGVeritas
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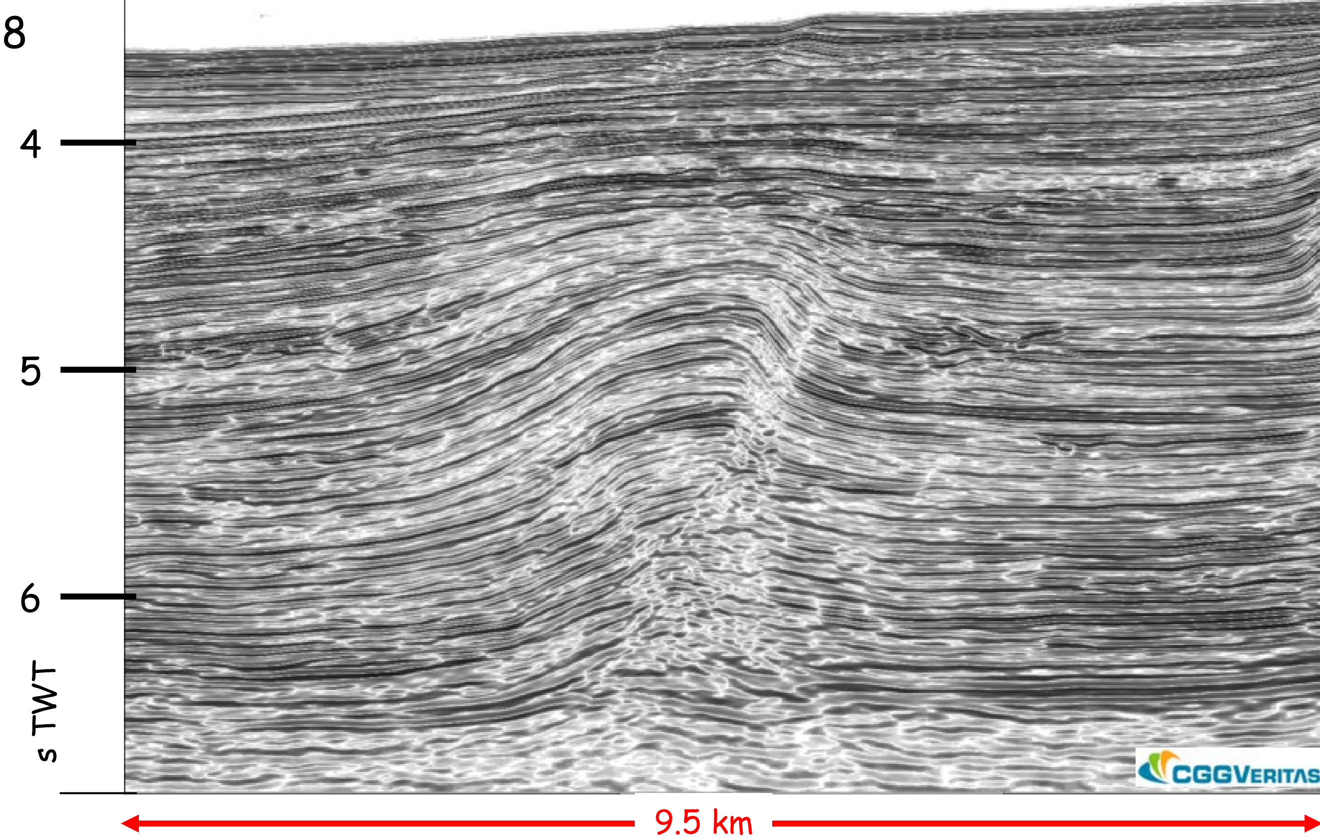
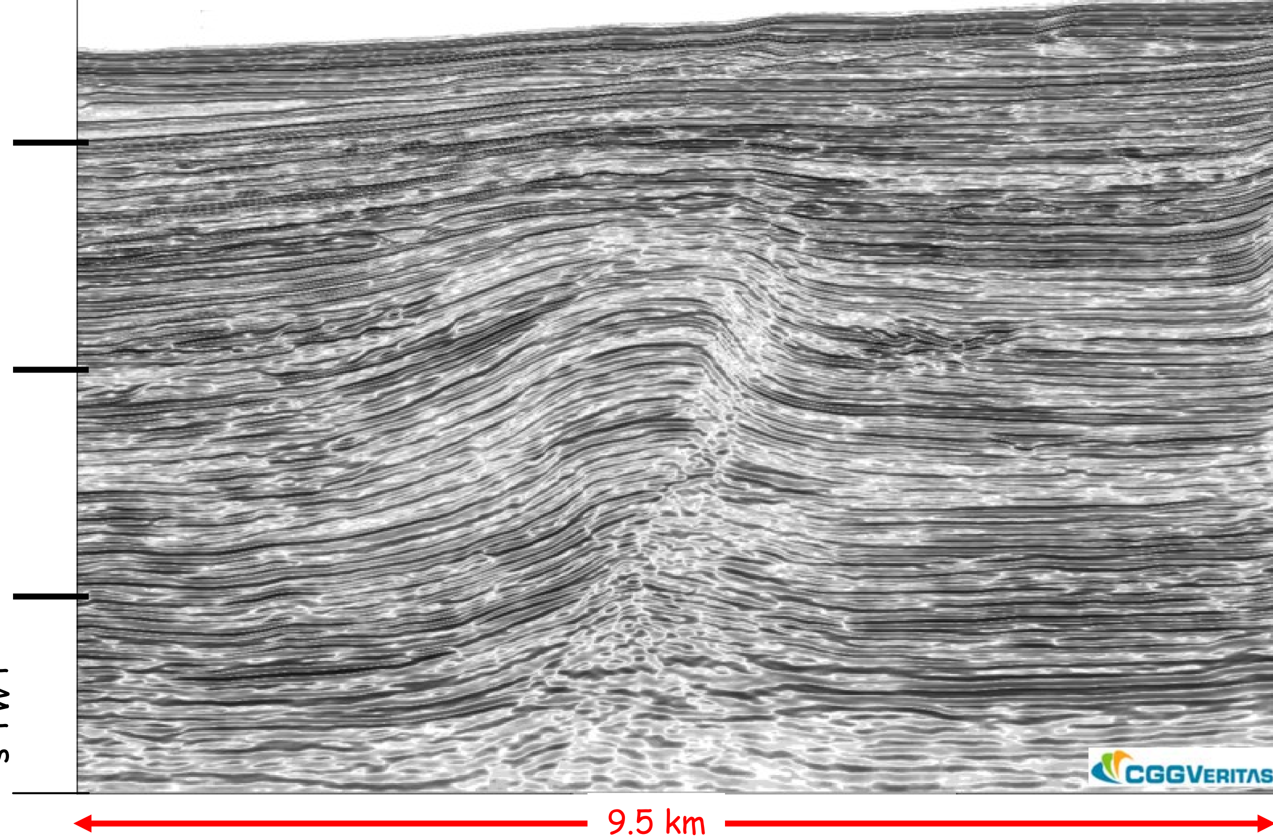
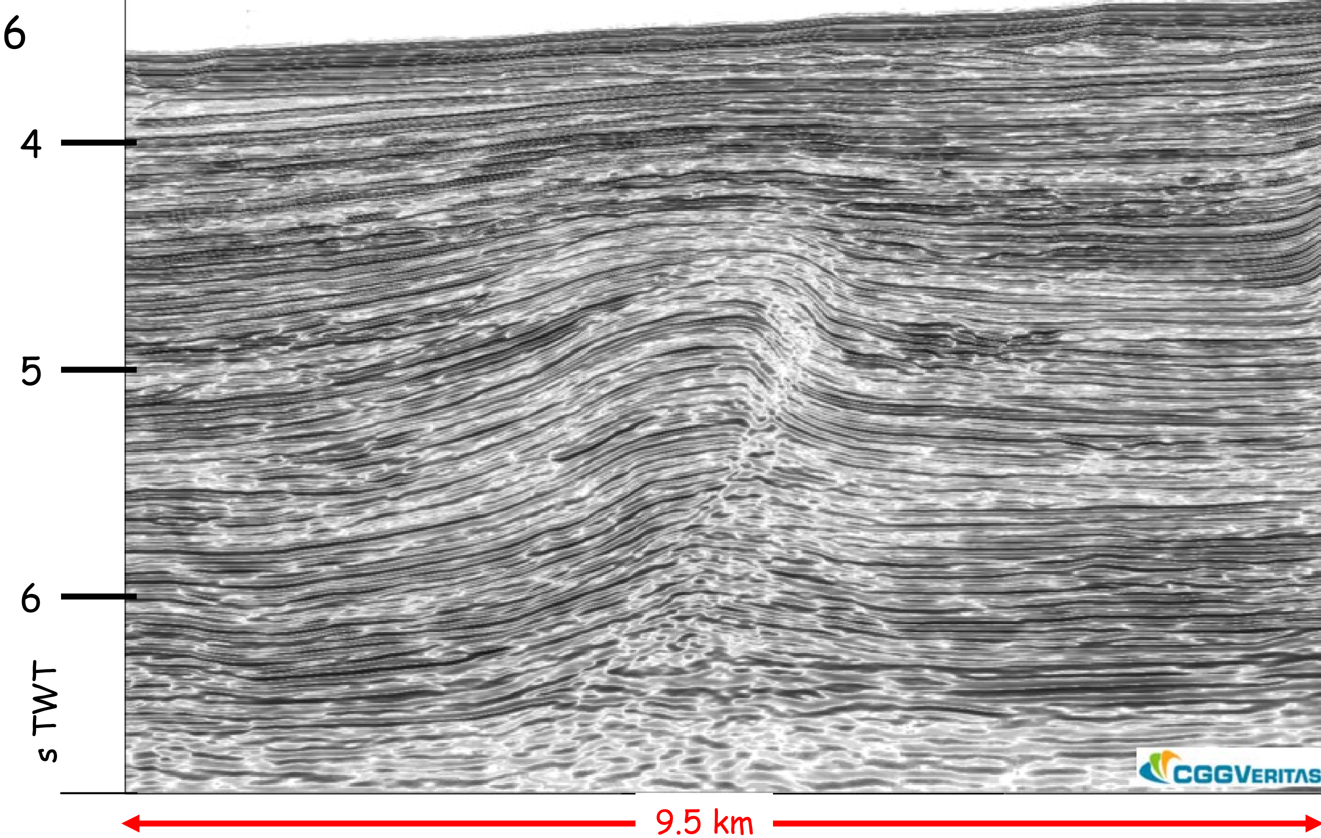
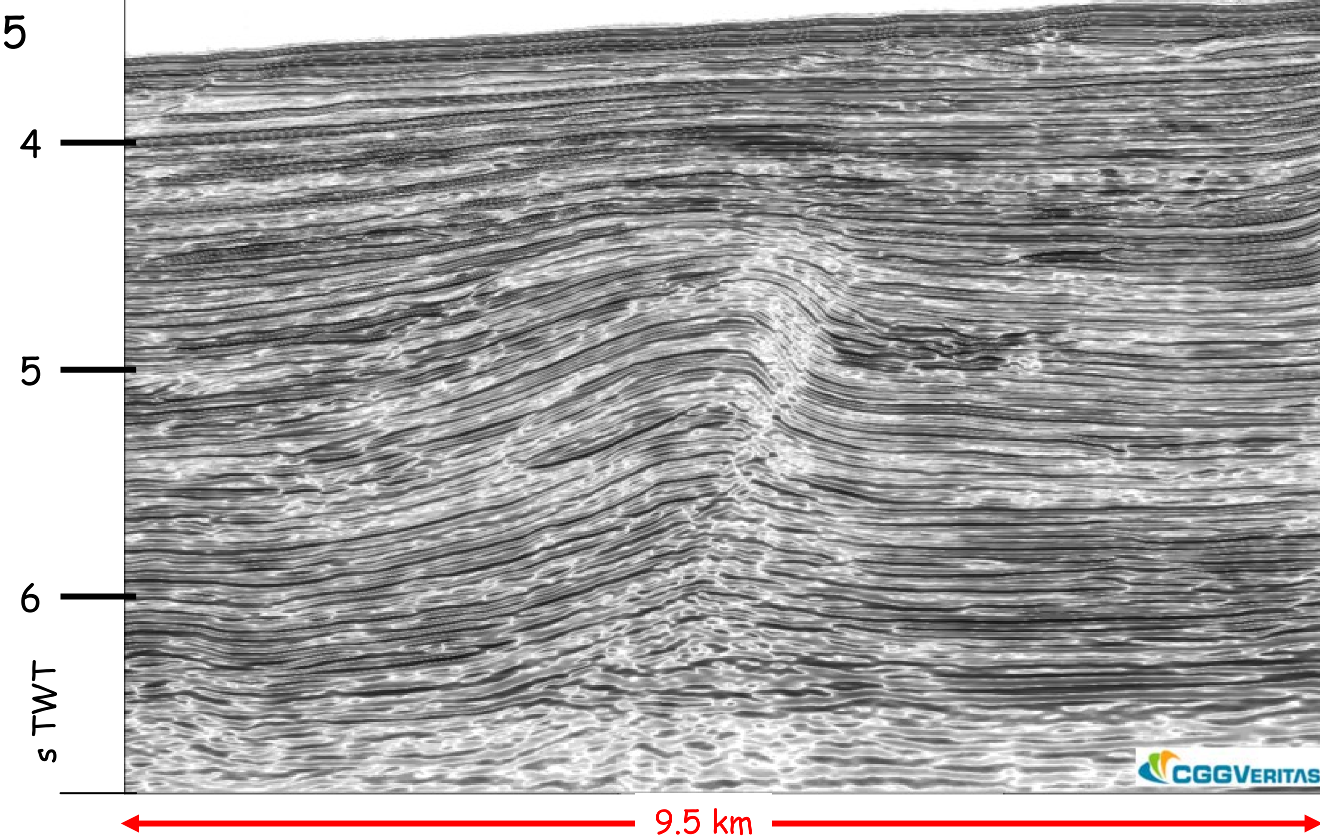

4
5
6
s TWT
9.5 km
CGGVERITAS

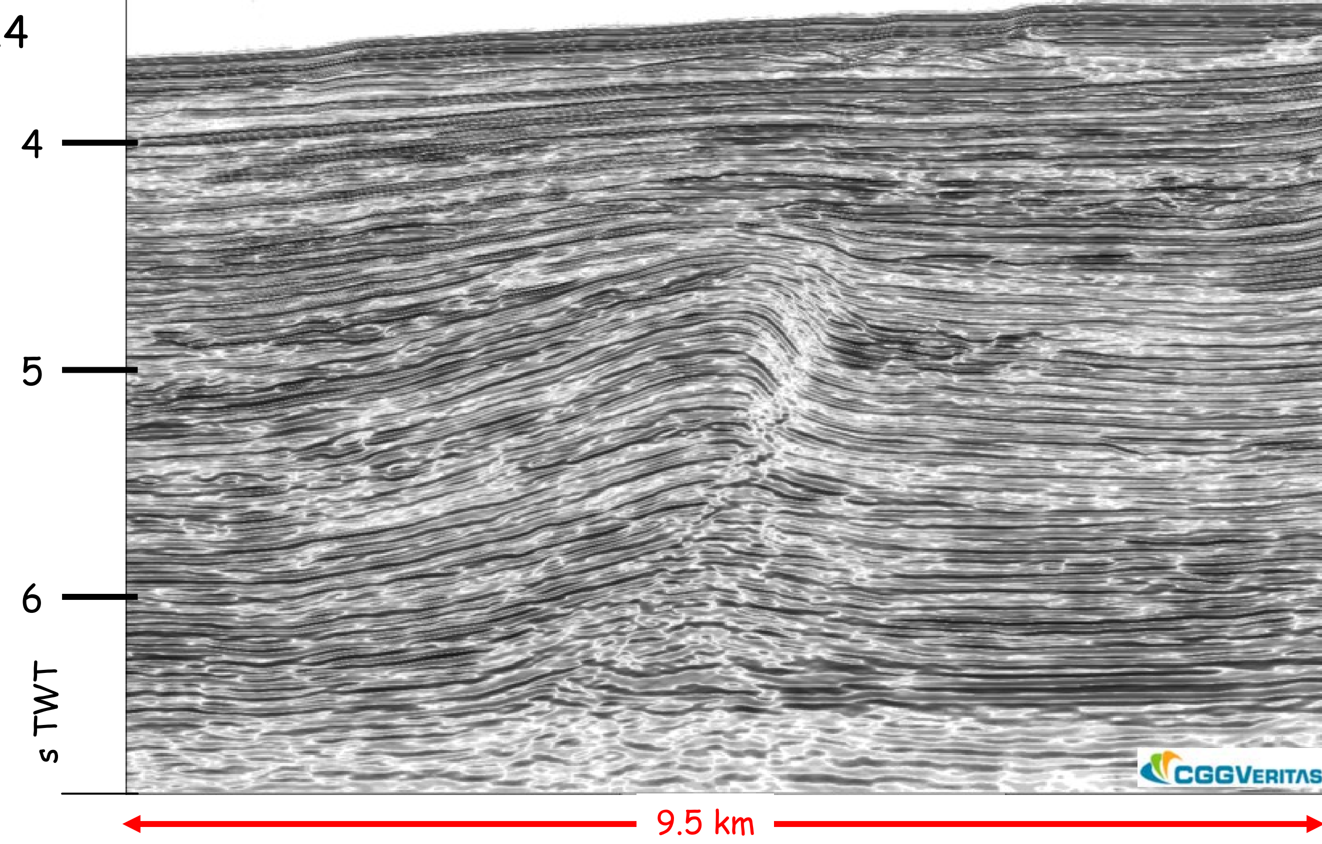
17

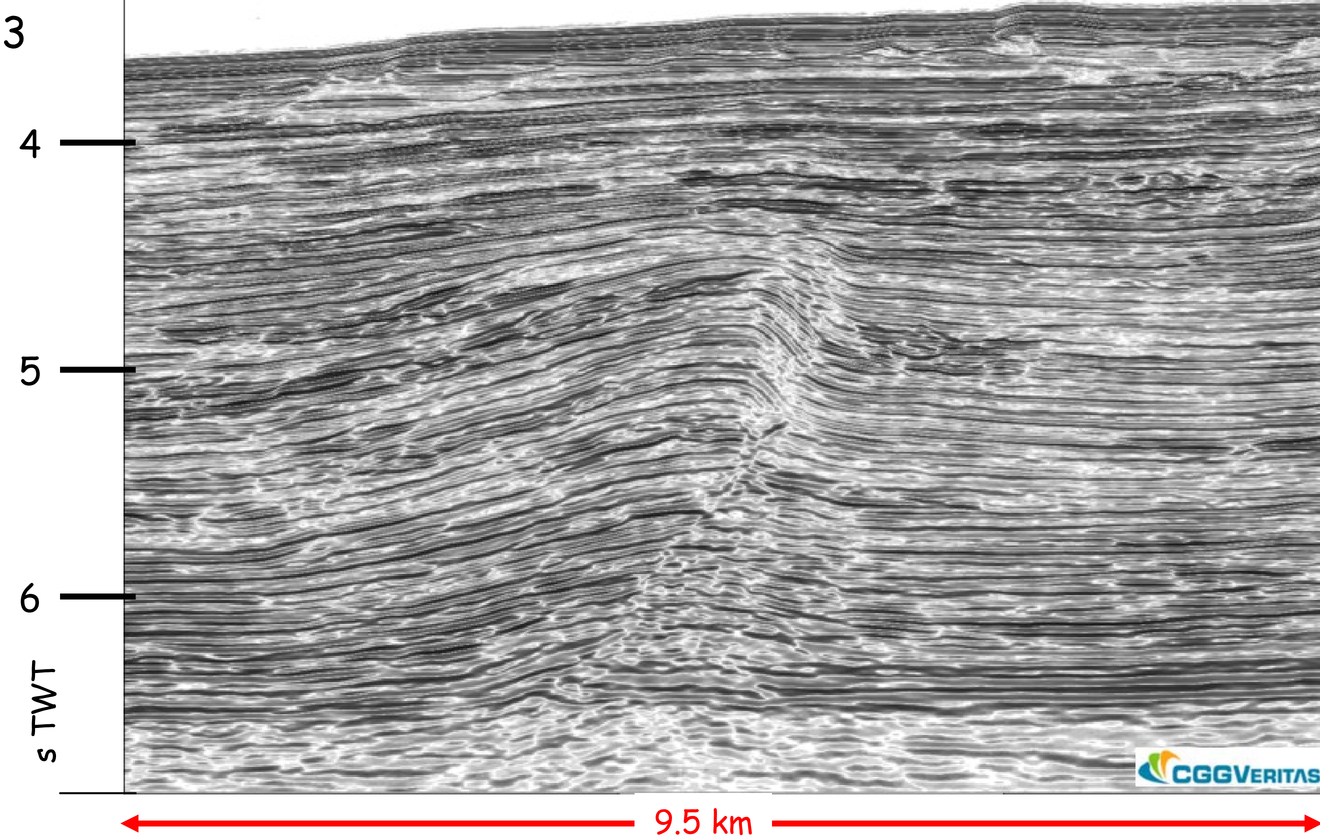


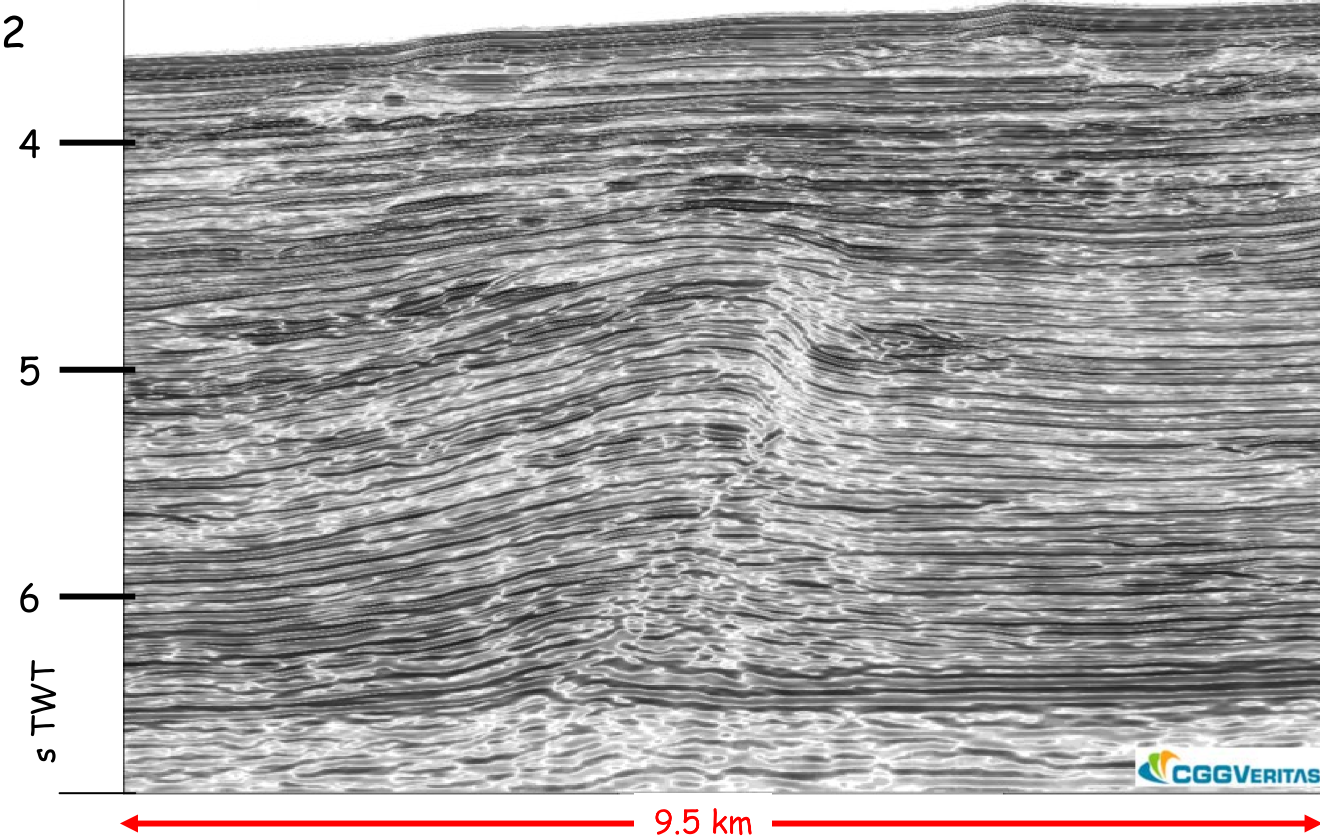

4
5
6
s TWT
CGGVeritas
9.5 km

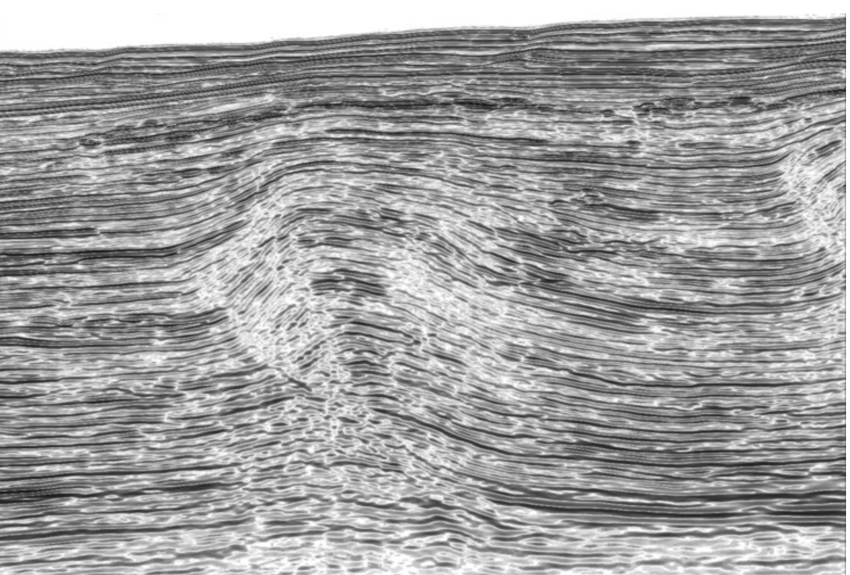

4
5
6
s TWT
9.5 km

14




4
5
6
s TWT
CGGVeritas
9.5 km

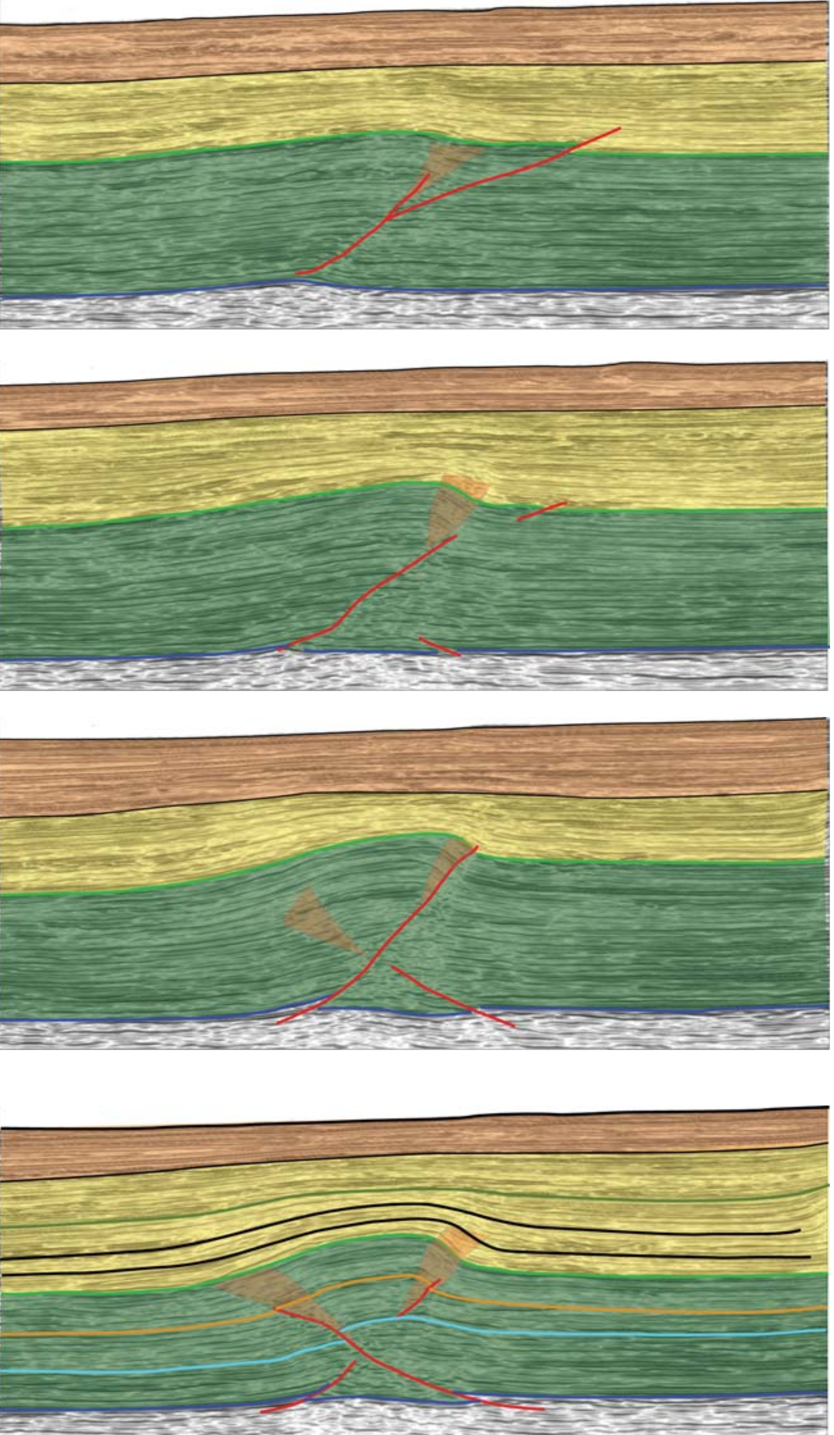


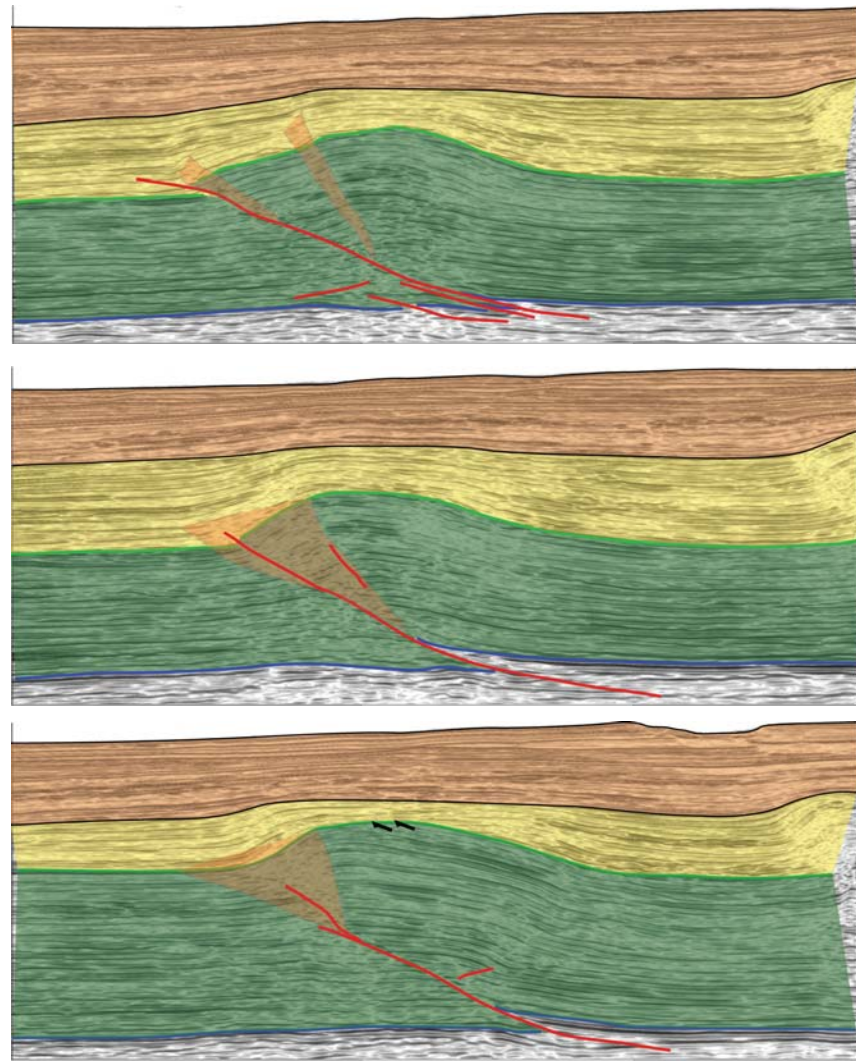


Shape of shallow layers - only weakly relates to fault geometry at depth

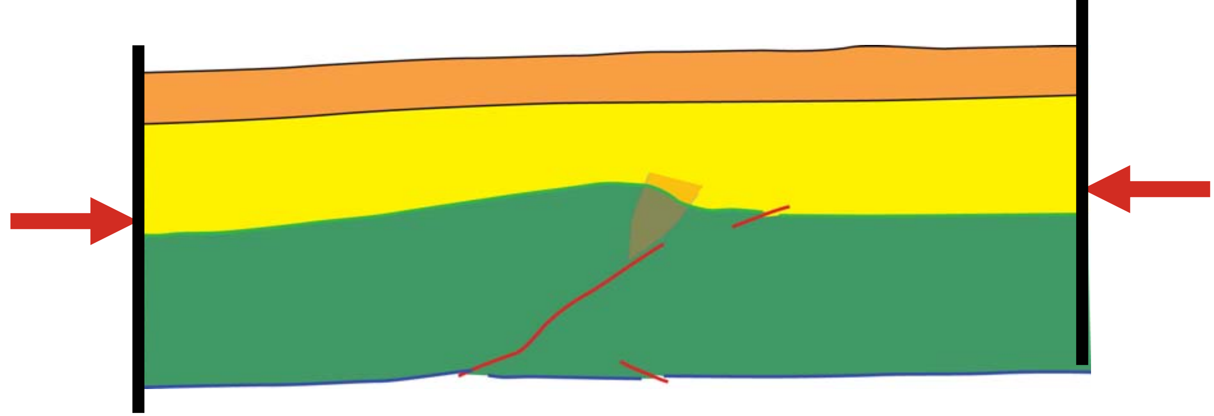
Evolves in 5.5 km

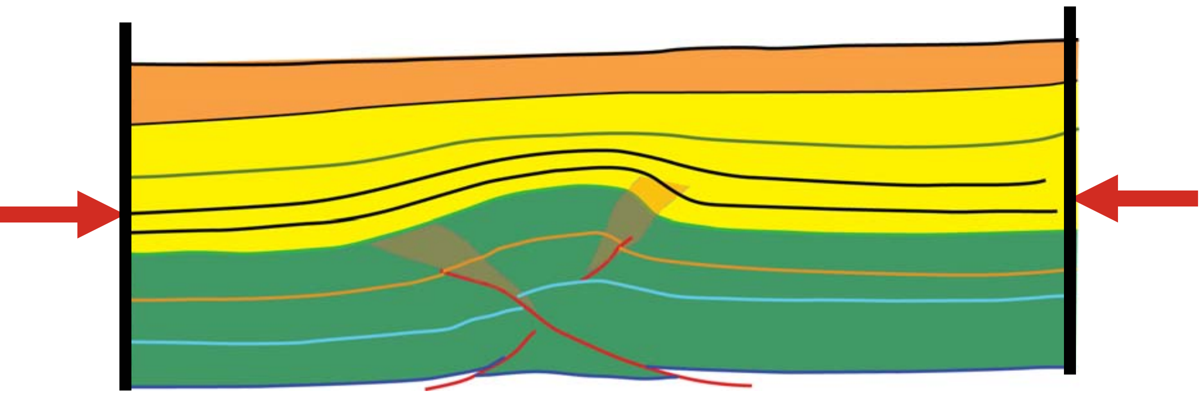
Styles of thrust-fold structures - Niger fan





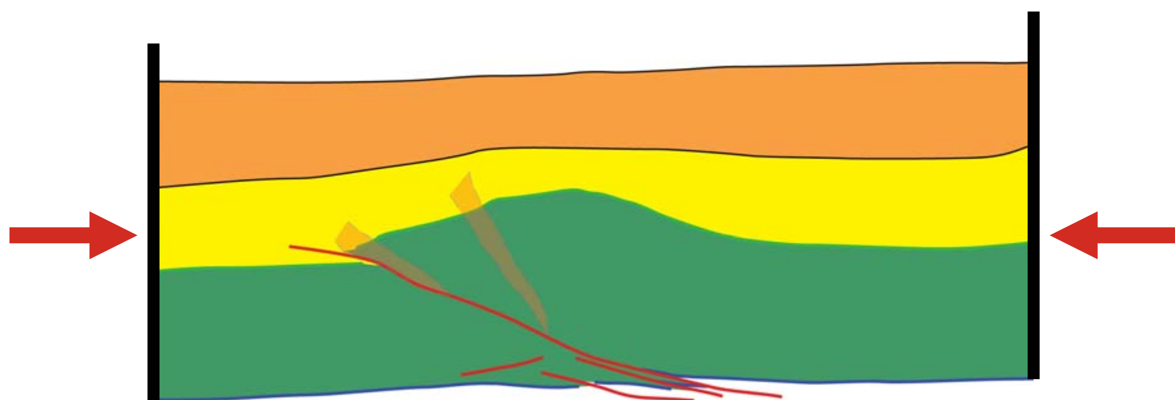
All scenes 9.5 km across, approx v=h





Layer-parallel shortening

Layers fail -
Buckling instabilities - evolve to thrusts (but may be overtaken by adjacent buckling layers….



There is no universal model (or strain path)… even for a single structure!

Coded models/workflows - large-scale structure
consequences

structural history
fault zone architecture/properties

PLAY THE FIELD - more models and analogues… BUT WHEN TO QUIT?